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ARCTIC ICE AND THE WARMING OF THE ARCTIC

by
H.N. ZUDOV

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ARCTIC ICE AND THE WARMING OF THE ARCTIC

Being Chapters VI and VII of

IN THE CENTER OF THE ARCTIC

*An Outline of the History of Arctic Exploration and of the
Physical Geography of the Central Arctic*

Translated from

Northern Sea Route Directorate Press, Moscow-Leningrad, 1948

by

E.R. Hope

Directorate of Scientific Information Service

DRB Canada

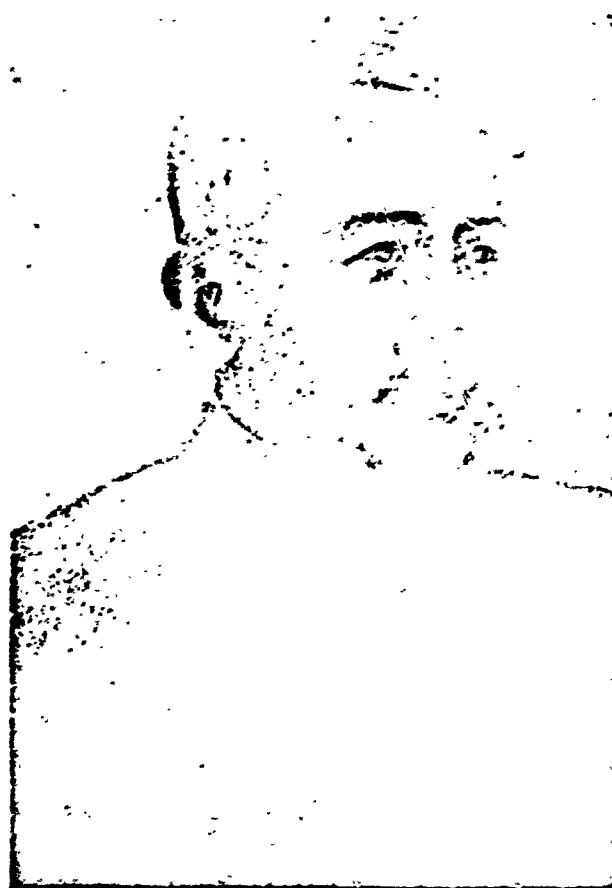
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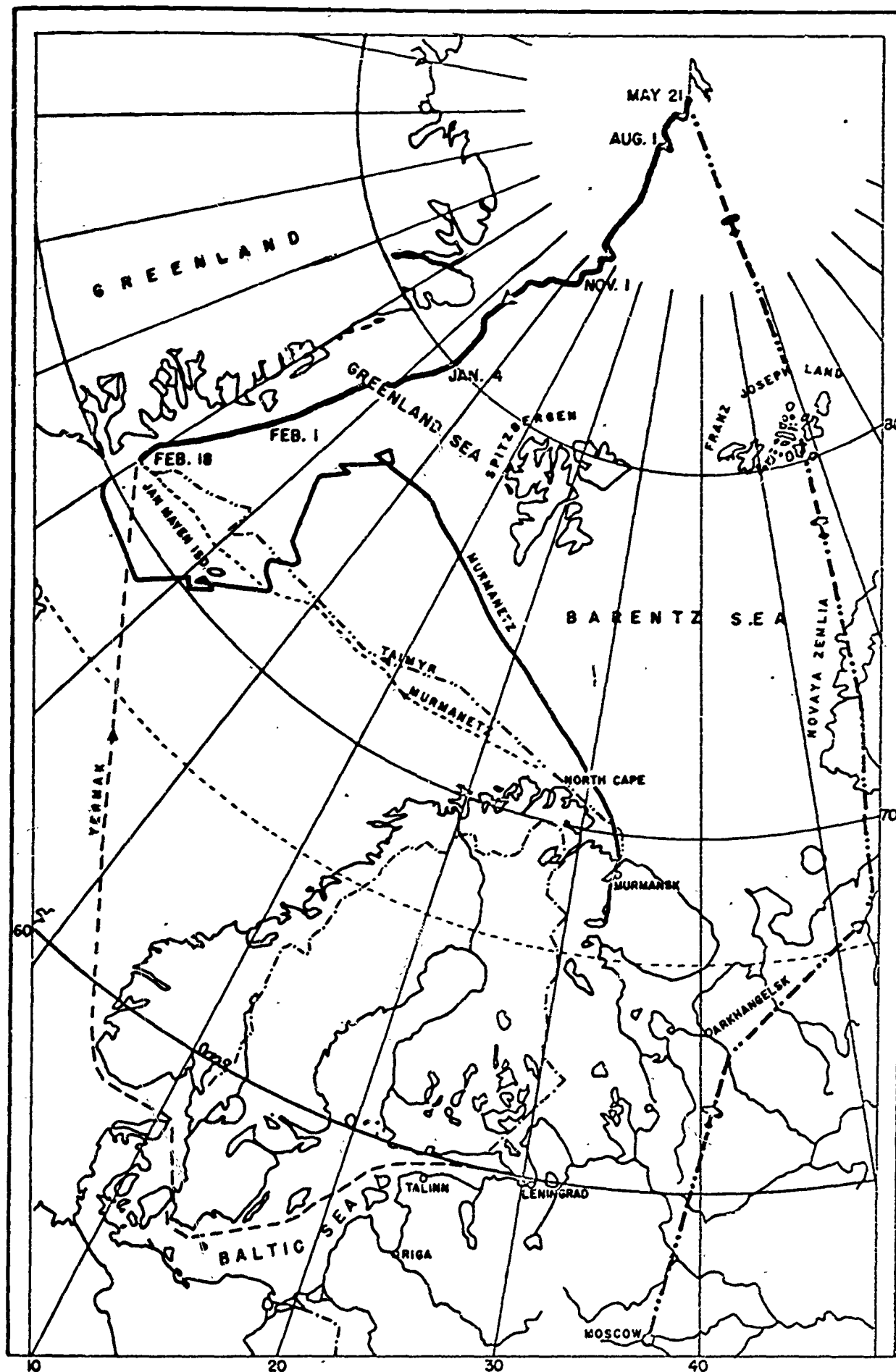
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Prof. N. N. Zubov



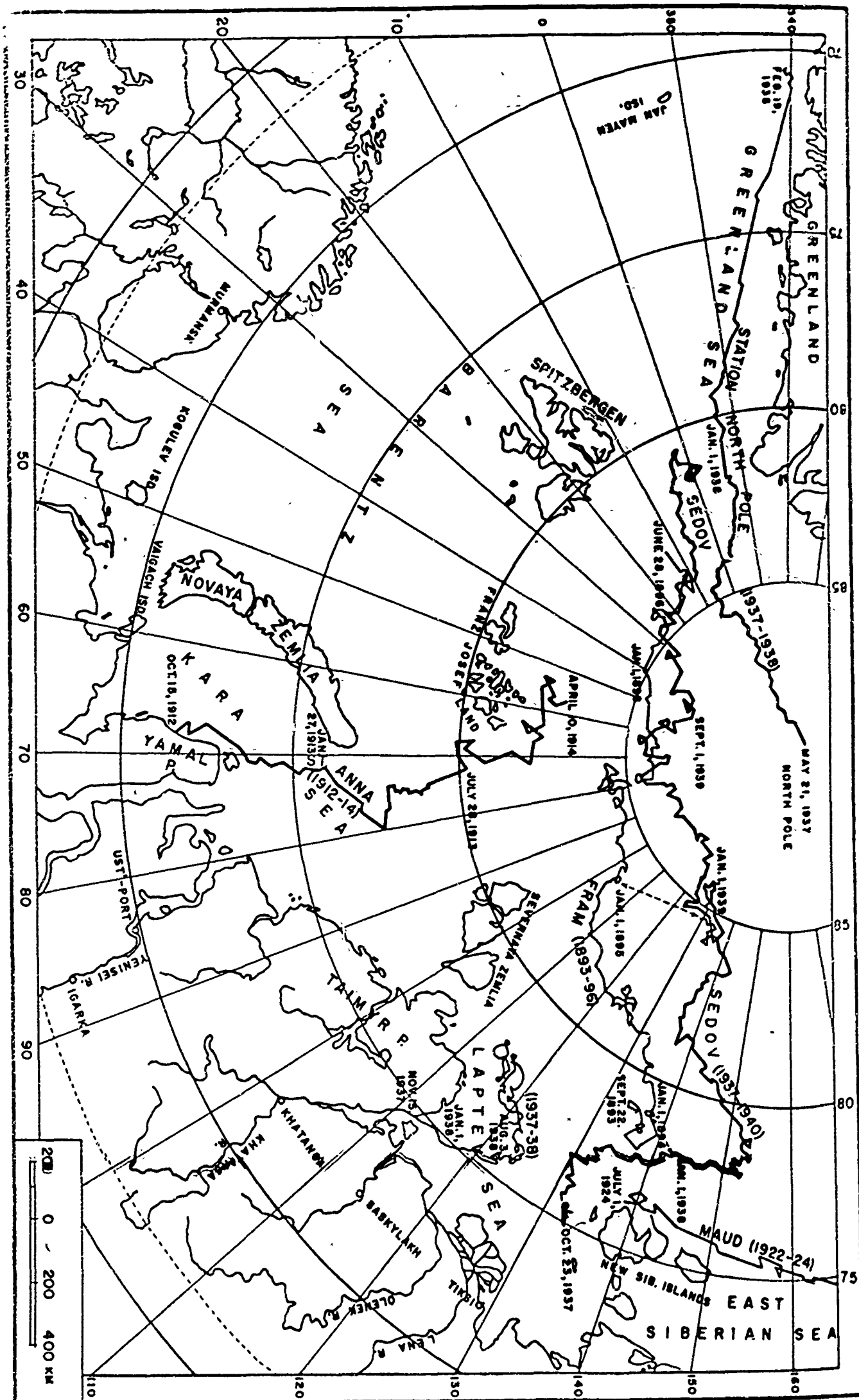
V. Yu. Vize (Wiese)
on board the Sibiriakov



MAP I. DRIFT OF "STATION NORTH POLE" AND ROUTES OF RESCUE EXPEDITIONS

- +--- ROUTE OF THE EXPEDITION'S AIRCRAFT
- DRIFT OF "STATION NORTH POLE"
- ROUTE OF RESCUE EXPEDITIONS

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MAP II. SHIP-DRIFTS IN THE ARCTIC OCEAN

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NOTE: The titles of the other chapters of this work (not here translated) are as follows:

- I A Bit of Geography and History
- II From the History of the Fight to Reach the North Pole
- III Russians in the Fight to Conquer the Arctic
- IV Some Physico-geographical Features of the Central Arctic
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IN THE CENTER OF THE ARCTIC

CHAPTER VI

ARCTIC ICE

1. How the ice is formed

The ice-cover of the seas of the northern hemisphere, at its greatest extent, takes up an enormous area---about 11,000,000 square kilometers. Each year in the summer the ice-masses decrease in total amount by approximately one-third. Those in the Central Arctic Basin occupy an area of about 5,000,000 square kilometers. This area is never free of ice.

On the basis of its origin and nature, ice may be divided in a clear-cut manner into three categories: river ice, glacier ice and sea ice.

River ice is distinguished by its brownish color and dirtiness; it is encountered not far from the mouths of rivers. This ice melts during the summer and does not count for much as far as sea conditions are concerned.

Floating glacier ice, in the form of icebergs, is formed by calving from the edges of glaciers which come down to the sea.

The bulk of the ice in the Northern Ice Ocean consists of greenish-white sea ice, formed from the sea water itself.

A very interesting property of sea ice is the fact that on the average it is only one-quarter as salty as the water from which it is formed.

Another surprising property of sea ice is that with the passage of time it gradually becomes fresher and at length can be used in the preparation of food. These properties of sea ice may be explained by its structure.

The formation of ice in the sea begins with the appearance of fine ice-needles, crystals of pure ice in a fantastic network. With the passage of time these crystals grow; the dissolved salt, the admixtures of organic or inorganic origin and the air bubbles which are found in sea water are concentrated in the spaces between the crystals. Thus once it is formed sea ice consists of crystals of pure ice with brine-cells and air bubbles interspersed between them.

The temperature-changes which take place in sea ice during its life-time cause variations in the volume of the brine-cells. Thus when the temperature falls the development of additional ice crystals increases the volume and causes cracking, the formation of minute fissures, through which the brine droplets gradually filter downwards. This decreases the salinity of the ice.

In new ice it is noticeable that the lower the air temperature and the faster the resulting formation of ice, the higher its salinity is. At very low air temperatures the brine is not only not able to flow downwards, but it is actually squeezed out onto the surface of the ice. As a result, the surface of ice formed at very low temperatures is always slightly damp with brine. At still lower temperatures the ice surface is covered with so-called ice flowers, of amazing beauty. These ice flowers consist of very fine salt crystals seated on the ends of ice crystals. This phenomenon is at times very clearly in evidence; many explorers have mentioned the difficulties which sledge expeditions encounter on sea ice which has been formed at low temperatures. Sledges will not slide on such ice: they drag as though they were being pulled over sand.

On the sea, ice-formation does not always commence at the surface. If the cold sea waters are strongly agitated by the wind or by strong currents, then ice-formation may begin in the depths of the sea or even at the bottom. In this process the water at first becomes as it were turbid; indeed this phenomenon is called ice-fog. The particles of ice forming in the depths of the water do not float up immediately to the surface, but are carried about from place to place by eddies. Subsequently the particles of deep-water ice, in the form of disks of very regular circular contour and with mirror-smooth surfaces, increase in size, freeze together, and at last rise to the surface of the sea.

For deep-water ice and anchor ice to form in the sea it is necessary, just as in the case of rivers, to have very low temperatures, strong agitation of the water by wind or currents, and no ice on the surface. As soon as the movements of the sea are impeded by surface ice or by deep-water ice rising to the surface, then in most cases the formation of deep-water ice ceases.

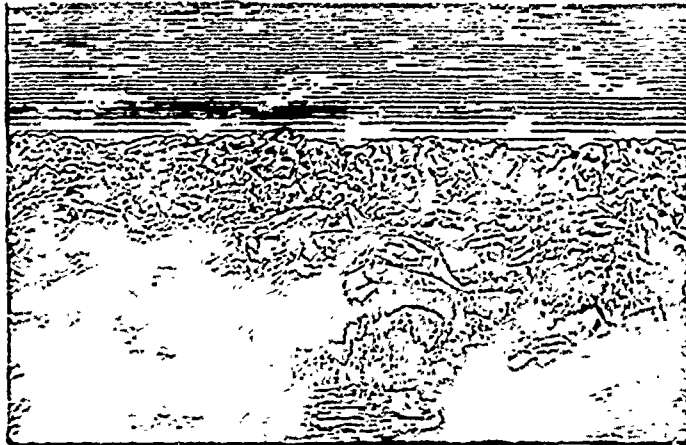
In the history of navigation cases are known of seafarers in the Baltic at the beginning of winter finding themselves surrounded on all sides by ice which suddenly rose from the depths of the sea. It is known too that on the rocky shores of Greenland, Labrador, and Spitzbergen anchor-ice often brings up with it to the surface fragments of rock and earth. In Newfoundland, ice is found at depths of 20-30 meters. On the coast of Labrador, a box of instruments was once brought to the surface by the anchor-ice. It was discovered that the box had belonged to a ship which sank in Hudson's Strait many years previously, some hundreds of kilometers north of where it was found.

Sometimes an initial crust of ice is formed by snow falling on the surface of the sea. This ice has a structure of its own and is distinguished by its white color: it bears the name of slush ice.

As we have seen, when the sea is quiet and there is no wind, small crystals of ice-needle type form on the surface. These initial formations gradually expand and unite, building up patches of thin ice film on the surface



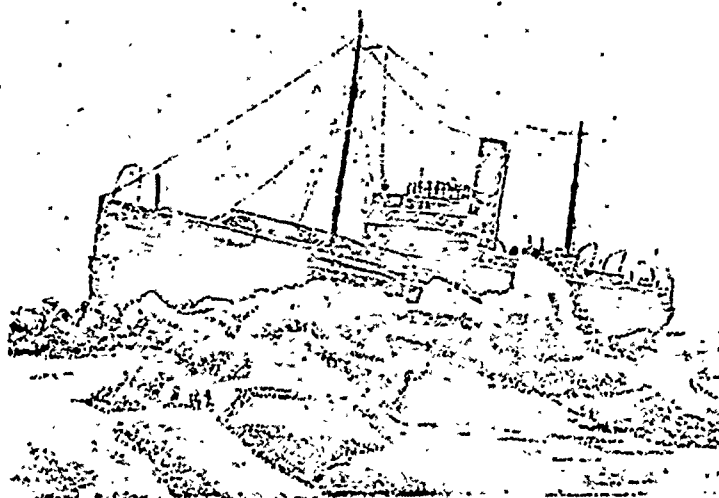
Discs of deep-water ice.



Palaeocrystic ice (accumulated ice of many years) on the north-west coast of Greenland.



Bottle ice.



The Sedov in the ice.



Station North Pole.

of the water. The look of this ice is reminiscent of congealing lard and it is called [in Russian] "lard ice", or simply "lard". It is usually of the dark color of lead, differing little from the color of the water in cloudy weather, and looks like worn-down ice.

The sea covered with "lard ice" gives one a very strange impression. The water looks heavy, like mercury. Since the formation of ice usually begins in separate and more or less sparsely scattered patches, the surface of the sea covered with "lard ice" takes on the appearance of watered silk.

When the sea gets still colder and is perfectly calm, its whole surface, particularly if the superficial layer is thin and almost non-saline, covers itself over with a thin shiny crust of ice --- bottle-ice. When a ship is proceeding through this bottle-ice a characteristic noise is heard, produced by ice-fragments which splinter off and fly to some distance; this noise reminds one of the tinkling sound of bottles breaking.

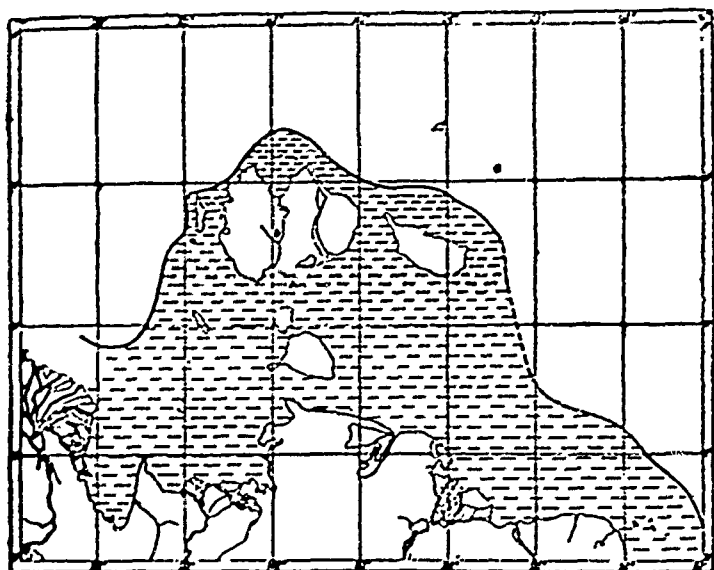
The initial formation of ice takes place somewhat differently when the sea is a little disturbed. Then it seems the process starts from many centers, and cakes are formed of almost perfectly regular shape, 30 - 50 cm in diameter. These cakes are rimmed with small ridges, which they acquire through rubbing one against the other. The ridges give the cakes the appearance of shallow frying-pans. In all languages this kind of ice is called pancake-ice or plate-ice. The ridges rise higher out of the water than the cakes themselves, and for this reason their color is whiter. With new pancake-ice, the sea looks as if it was covered with a white netting.

After the surface of the sea has become covered with a thin layer of ice, its thickness increases more rapidly the lower the temperature of the air, and more slowly the thicker the ice becomes. It is reckoned that under Arctic Basin conditions the thickness of ice formed in any one year by natural accretion does not exceed two or three meters. The ice-fields acquire their greatest thickness through rafting, the piling up of floe on floe. Our Arctic men indeed make a distinction between ice-fields on this basis ... growth-fields and rafted fields.

According to its location, sea ice is divided into fast ice, floe ice, and pack ice. In the Arctic Basin in the winter season, fast ice accounts for fifteen to twenty percent of the whole ice area. Ten to fifteen percent consists of floe ice. The remaining area, that is about seventy percent, consists of pack ice, which like floe ice is free-floating and in continual motion. Pack ice fills the central portion of the Arctic Basin; it is for the most part fringed by floe ice, but nearer to the shore ... in the winter season ... it is bordered by the fast ice.

Fast ice is the shorebound ice which forms along the coast in winter, reaching a thickness of about two meters by the end of the winter. In summer, part of the fast ice melts in situ, and part of it breaks off and is carried out to sea.

It is reckoned that the fast ice in winter extends off shore as far as the twenty-five-meter depth contour. It attains its greatest development on the coast of Siberia, in the longitudes of the mouth of the River Yana,



The fast ice in the region of the New Siberian Islands.

where it may extend nearly four hundred kilometers northward from the coast. This is explained by the shallowness of the water here and by the existence of numerous islands. We call this region the fast ice sector.

Floe ice, as its name indicates, is in continual motion both summer and winter. Part of it disappears during the summer. Part of it survives and is incorporated into the re-forming ice-masses.

In floe ice we may find formations of the most diverse origins, shapes and sizes. The floe-ice zone is thought to extend approximately from the 25-meter

contour-line (the outer limit of the fast ice in winter) to the boundary between coastal and deep sea water ... approximately the 1000 meter depth contour.

Pack-ice is the ultimate form of sea ice. It is made up of great fields of comparatively even ice from three to five meters thick. These fields are rimmed with hummocks and in some places traversed by ridges eight to ten meters in height. The ridges are formed by floes squeezing together and piling up, and they indicate the position of so-called lines of hummocking.* In some areas the ice-pack may be a very wilderness of tortured and piled-up masses of ice, in which it is impossible to detect any regularity of formation; these are called areas of hummocking.**

Pack-ice is characterized by its uniform composition and absence of foreign admixtures (brine cells and air bubbles). Several processes are necessary in forming it: the natural formation of ice, the thickening of the field by floes rafting one upon the other, the structural changes in the ice which are caused by periodic temperature-variations, the consolidation which is caused by periodic cycles of packing, and finally the levelling-off of the upper and lower surfaces of the pack.

The last-mentioned process begins when the ice reaches such a thickness and massiveness that further hummocking is impeded. Snow is blown about by winter storms and gradually fills up the depressions in the ice-surface.

* Lines of pressure. (Tr.)

** Pressure areas. (Tr.)

The Arctic sun, which never rises very high over the horizon,* acts first of all and indeed almost exclusively on any kind of unevenness or high spot in the ice, melting it down and smoothing it out. In this manner the upper surface of pack ice is levelled off.

Theoretically the under-surface of the ice should be much more uneven than the upper. Actually, the density of pure ice (free of any foreign admixture such as salt, dirt, or air-bubbles) is equal to 0.9176. The difference in density of the ice and the water in which it is floating is such that usually a mere one-fifth to one-seventh of the total thickness of an ice-field shows above the surface of the sea. Consequently the weight of a hummock five meters high should be balanced by a boss on the lower surface of the ice extending to a depth of about thirty meters.

However, as observations show, the temperature of the lower surface of the ice is very near to the freezing point of the sea-water, and at such temperatures the ice has almost no strength and the slightest pressure causes it to crumble. The result is that the underwater bosses corresponding to surface hummocks very soon break up; the hummock then settles by its own weight and creates a new under-water boss beneath it, which again breaks up. Thus there takes place a simultaneous levelling of the upper and lower surfaces of ice-fields, a process which is usually more marked in summer but does not stop even in winter. It is called the isostatic levelling of ice-fields.

Although the stretches of open water between the separate fields of a pack are insignificant in extent (even in autumn they do not constitute more than one or two percent of the area), they nevertheless permit some movement of the fields even in winter time.

The mass of the ice-field on which Station North Pole was located was, at a modest estimate, ten million tons. If such an ice-field acquires even a slight motion (under the influence of wind or currents) and drives against the shore, or against another ice-field which is either stationary or moving at a different speed, it is easy to understand that at the points of contact even ice of enormous thickness will be smashed up, forming huge hummocks.

Of winter hummocking Badigin, the Commanding Officer of the Sedov, wrote:-

"It is difficult to describe these noises; sometimes they remind one of the howling of the wind, sometimes of the monotonous roar of a motor, sometimes of the growls of some unknown animal, sometimes of a breaking surf."

On the other hand all observers are struck by the surprising quietness of summer hummocking, which may be on a scale more vast than in the case of winter hummocking. Immense monoliths of ice split off, rear up and topple, with no audible noise even under perfectly windless conditions.

The tumult and noise which accompany winter hummocking and the absolute silence of summer hummocking may both be explained in terms of the

* At the Pole, the sun of course cannot rise higher than $23\frac{1}{2}$ degrees above the horizon. At 80° N it cannot be higher than $33\frac{1}{2}$ degrees. A level ice-surface would therefore reflect nearly all the solar radiation. (Tr.)

mechanical properties of the ice. The strength of ice is very much dependent on its temperature. At -90°C its strength is approximately equal to that of well-fired brick and increases very little as the temperature is lowered below that point. As the temperature rises toward the melting point its strength rapidly declines; at still higher temperatures the ice turns into a porridge-like mass.

The temperature of sea ice formations is continually changing, but that of the under-surface remains constant, approximately equal to the freezing point of the sea water, that is, -1.6 to -1.8°C . The temperature of the top surface approximately follows that of the atmosphere, sometimes dropping below -40°C . Consequently the ice at the bottom of the field does not change in bulk, while at the upper surface it is either swelling or shrinking by reason of thermal expansion and contraction. For instance, the top of Station North Pole's ice floe was capable of changing its horizontal dimensions by one or two meters in the course of a year, solely through the effects of temperature variation. Such variation in size causes fissures to form, a process which is accompanied in winter-time by sounds reminiscent of the sharp crack of a rifle. These sounds have been heard by all Arctic explorers; they were heard by the men of Station North Pole and by those of the Sedov, who during their sojourn on the ice learned to distinguish the various noises which fill the air of the Arctic Basin in the winter season.

2. How the ice disintegrates.

During the winter the dimensions of an ice-floe may be increased by normal formation of ice, by rafting, or by its freezing to other floes. Ice fields of huge size may be formed, which then may from time to time be broken up by severe winter storms. In area and thickness the Arctic ice-cover reaches its maximum development in May; but long before this a process of internal melting has begun, a process which reveals itself first of all in the structural weakening of the floes.

This process takes place because, as we already know, sea ice consists of crystals of pure ice with an interspersion of brine-cells. These cells reach their minimum size when the temperature of the ice reaches its minimum. As soon as the temperature begins to rise, the brine-cells increase in size and the solution they contain decreases in concentration ... the ice begins to melt as it were from inside out.

The rise in the temperature of the ice is caused by absorption of heat from the atmosphere and from the surrounding water to which, as soon as the sun begins to show itself more and more above the horizon at the end of the Arctic night, there is added the absorption of solar heat.

The absorption of solar heat by the ice has some quite interesting features, as we have already noted. The snow surface is quite a perfect reflector, while water on the contrary is a quite perfect absorber of solar energy. Hence with the arrival of spring and summer the melting of the ice proceeds most rapidly where there is the most open water between the floes. The water absorbs solar energy and passes it by contact to the ice floes, thus causing a warming of the latter.

On ice fields, solar heat is absorbed most intensely by the dark-colored particles which are found on the surface of the ice. In the case of coastal ice these particles may consist of dust brought from land by the wind. In the case of ice-floes out at sea, many of the particles are of organic origin: tiny organisms which, alive or dead, have in one way or another become frozen in the ice.

Nansen pointed out that since the melting of old ice takes place principally from the top while the accretion process goes on below, all foreign admixtures gradually move upwards and finally come out on the surface. The particles then form centers around which the absorption of solar energy and the melting process take place.

During the Arctic summer the presence of dark particles of all kinds in the ice is very clearly shown by the color of the fields.

Thus it has been observed that with the arrival of warm cloudy weather the surface of the ice looks muddy and smooth. In clear sunny weather the dark particles on the surface absorb the solar radiation, become warm, and thaw out little pits beneath them; they sink into these pits to a short distance below the surface level. This means that in such

weather the ice surface becomes porous and looks snow-white, as though covered with newly fallen snow.

Nevertheless, no matter how great the reflecting powers of snow, it absorbs some part of the solar warmth. At first, the top particles of snow are subjected to the action of the sun's rays; they fuse together into a solid mass which reflects very strongly. The snow under these conditions shines with a blinding glare which causes acute inflammation of the mucous membrane of the eye, the so-called snow-blindness.

This strong reflection makes the horizon indistinct even under a cloudless sky, and strong refractive effects may be observed. If the sky is covered with a thin layer of cloud, then the whole atmosphere seems to be filled with a peculiar silvery shine which reminds you of light reflected from a polished silver plate.

In spite of the fact that in the early spring of the Arctic regions the temperature of the air may never rise above -10°C and sometimes may fall below -30°C , the first droplets of brine begin to appear on the southward slopes of the ice masses, and the sharp edges begin to melt and round off. As the air temperature further increases and the sun rises higher and higher above the horizon, the surface layer of snow becomes saturated with water and it acquires a greater capacity for absorbing solar heat. Each time there is a sudden cold spell, an ice-crust forms on the now surface. This ice-crust plays the same role as the glass over a greenhouse.

Its effect is that a gradual accumulation of heat takes place, raising the temperature of all the sunlit parts of the ice. Inside the ice this heat is absorbed not so much by the ice crystals as by the inclusions of foreign matter among them. This by the way explains the fact that the ice formed on a pond under quiet conditions has a characteristic honeycomb appearance when it is melting; also the fact that ice of any origin, marine or otherwise, will when finally disintegrating break up into separate needles, vestiges of the crystals.

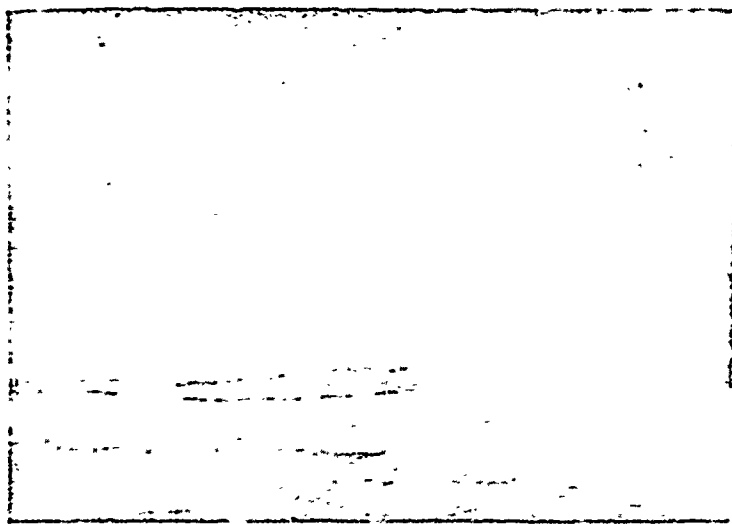
With the passage of time there are formed on the ice surface, first of all dark spots, then small lakes called melt-water pools. In spite of occasional spells of freezing these pools continue to grow in size because of the protective effect of the ice crust which forms over their surfaces at such times. I have often observed pools of melt-water (with temperatures above $+1^{\circ}\text{C}$) covered with a crust of ice as much as 10 cm thick.

In pure sea ice the centers of absorption of the solar energy are the brine-cells. They gradually increase in volume as their temperature rises; this speeds up the downward movement of the brine and the desalinification of the ice. Thus, through solar energy and heat conduction, changes take place deep within the ice. At first they scarcely show up at all so far as the outer shape and size of the ice-formations are concerned, but they diminish its strength very much. As seamen say, the ice gradually becomes rotten.

Meanwhile the pools of melt-water on top of the ice continue to grow, sometimes slowly, as when they are covered with ice during freezing spells, sometimes with considerable speed, as when they are completely free

of ice. The melt-water penetrates into the fissures which are found in sea ice, but it soon strikes layers of ice which are still at that season considerably below the freezing point. The water then freezes, plugging up the fissures and preventing the bulk of the water from draining away.

Thus the first thawing of the snow on top of the ice leads to the formation of pools of fresh water which gradually increase in size and link up one with another until at last they make the surface of the melting floes look like a sea covered with drifting ice. All that shows above the water-layer (which may reach a depth of one meter or more in the southern parts of the Arctic Basin) are the crests of hummocks and blocks of old paleocrystic ice. These springtime ponds on the ice are still less distinguishable from the sea itself if there is a wind which ripples the surface and raises a light swell.



Steamer replenishing its supply of fresh water from melt-water pools on the ice.

The formation of these fresh-water ponds on sea-ice floes during the summer is not restricted to the southern regions of the Arctic Ocean, where such ponds have long served as a source of fresh water for seamen. During the voyage of the Sadko in 1935 we often took on board a hundred tons or so of fresh water from a single lake on the ice in the northwestern part of the Barentz Sea.

During the drift of the Fram, the crew amused themselves by sailing small boats on the lakes which formed in summer on the ice fields. The crew of Station North Pole also observed such lakes on their ice-field and were obliged to construct special drainage channels for them. The largest of these lakes was 200 by 400 meters in size and had a depth of 2.5 meters.

Any foreign substance in such ponds is naturally washed down into the deepest parts. Likewise organic life accumulates and develops in these sumps. Because of the darker color of the accumulations, it is here that the absorption of heat is most intense. Gradually the sumps deepen until they get down to the sea water underneath. Then the whole volume of melt-water pours out below the ice, and in a day or two the ice surface dries off and emerges from the water. There remain only smaller ponds, some with their surfaces above sea-level (no sink holes; water fresh), some with their surfaces AT sea level (sink holes formed; water in them salty).

The top of the ice after the surface water has drained off is very uneven, riddled with sink-holes and stripped of its winter snow-cover. But in time, particularly when fine weather sets in, dark particles on the surface once more absorb the solar radiation and create a porous upper layer. Thus is formed the summer snow-cover of ice-fields.

As was noted by Nansen and verified by the men of the Sedov, the draining away of the melt-water results in the formation, on the underside of sea ice, of a layer of pure fresh-water ice. This fresh-water keel ice is formed by the run-off of fresh water coming in contact with the sea water, the temperature of which at this season of the year is about -1.8°C . Thus according to the Sedov observations, melt-water flowing out under the ice and freezing to the under surface added 5 to 55 centimeters to the thickness of the floes in the course of the summer of 1939.

The melting of the ice is particularly speeded up as soon as the atmospheric temperature rises above -2°C . The ice is gradually weakened to such an extent that one or two storms are enough to break up fields which shortly before possessed massive strength. Most remarkable is the fact that from the external shape it is very difficult to say how far decay has gone in a given ice-field. Sea-ice formations melt as it were from the inside out, and the last thing they lose is their figure.

As the observations of the Soviet Arctic stations have shown, open water may appear in straits like Matochkin Shar or Yugorski Shar when the ice-cover is still not less than a meter thick.

With the break-up of the ice-fields during the Arctic summer, the stretches of open water between floes are increased in size by the buffeting of storms, and this gives the individual ice-fields some freedom of movement. At sea one never finds two ice floes exactly alike. The wind and the ocean currents, prevailing and periodic, get a different purchase on each floe and set them in motion in different directions and at different speeds. Hence frequent collisions are inevitable; this causes hummocking and still further opens up the channels between floes. The more open water there is, the more violent are the movements of the individual floes relative to one another, and the more strongly in evidence are the processes of melting and disintegration.

Surface water warmed by the sun's heat becomes chilled on contact with an ice-mass, becomes denser and in consequence sinks to the bottom. More water flows in to replace it. The result is that a continuous convection current is set up, warm water flowing toward the ice-mass on the surface, and, at some depth beneath, cold water flowing away from it. Thus every mass of ice in the sea is a kind of automatic pump.

A similar thermic circulation is set up in the air. Over the open water there is an evaporation and a cooling of the surface layers of water. When the moisture-laden air passes over the cold surface of the ice floes the water vapor condenses and the heat which was taken up from the water in evaporation is given off again. These processes are inevitable whenever ice and water are in contact. The condensation of water vapor above the ice causes the fog which is so frequently seen over Arctic ice floes in the summer season.

3. The Limiting Thickness of Ice-formation

Very different sets of characteristic data might be used to describe the climatic peculiarities of each region of the Arctic Basin. For understanding the ice-cycles, however, we are most interested in two data, namely:-

1) The winter increase in the thickness of the ice (aside from that caused by hummocking).

2) The summer decrease in the thickness of the ice.

Palaeocrystic ice cannot continue by natural growth to increase in thickness without limit. If in any region of the ocean the number of degree-days of cold (that is, the sum of the daily means of below-zero air temperature) and the amount of summer melting remain constant from year to year, then the thickness of an ice-field which is growing only by natural freezing tends toward a quite definite limit known as the limiting thickness of growth-fields.

Thus with 6000 degree-days of cold and with a summer decrease of ice-thickness amounting to one meter, the thickness of ice formed by accretion cannot exceed 265 cm. With the same number of degree-days of cold and a summer melt of 30 cm, the limiting thickness of the ice rises to 790 cm. The limit exists by reason of the fact that the thicker the ice the more slowly its thickness will increase at any given air temperature. Ice floes reach the limiting thickness characteristic of the Arctic region in question when exactly as much ice is freezing on in one winter as is melting off in one summer.

Let us suppose for instance that a hummock with an above-water height of five meters and an underwater draft of about twenty-five meters ... which are not unusual dimensions ... is carried by wind and current into a region of the Arctic where the limiting ice-thickness is three meters. Gradually (not within a single year) the thickness of the hummock will be decreased both from above and from below until after some years' time the height of the part of the hummock above water level will become equal to 50 cm and the draft of the underwater part 250 cm. If to the same region there drifts an ice floe with a total thickness of 1.5 meters, then in the course of time its over-all thickness will grow to as much as 3 meters but no more.

Thus the limiting ice-thickness for any given region of the Arctic is a completely determinate climatological characteristic of that region, involving the two factors of winter growth and summer melting.

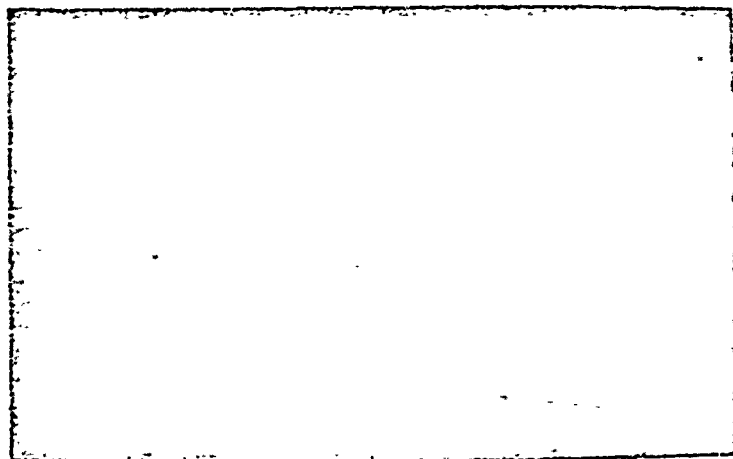
In studying the question of how soon under natural conditions the floes will reach their limiting thickness, I had occasion to analyse a very interesting phenomenon, namely the equilibrium of ice and water in contact.

Suppose we put a piece of pure ice into a certain volume of pure water which is insulated perfectly against any exchange of heat with its surroundings. The ice may either grow or shrink in volume, depending on the temperatures of the ice and water. The moment when the temperatures of the two become equal is also the moment when conditions become such that they may exist side by side in equilibrium.

This is a fact which has very important consequences. In some books on physics it is asserted that the temperature 0°C is the melting point of pure ice or snow; other textbooks say that it is the freezing point of pure water. Both these definitions are inaccurate.

The temperature 0°C is the temperature of pure water at which a piece of ice put into it will neither grow nor shrink in size.

This is a definition which will give us a proper concept of the temperatures at which sea water freezes and sea ice melts; these temperatures being of course dependent on the salinity.



Hummock barrier off-shore.

Let us now proceed to suppose that a certain ice floe is carried by the wind from the region where it was formed into a different region. Then depending on the relation between the temperature of the water and that of the ice-mass, and depending also on the relation between the thickness of the floe and the limiting ice-thickness in the new region, the floe will either increase or decrease in size; in other words it will either grow a bit or melt a bit off.

But any accretion to the ice will entail an increase in salinity of the surface layers of the water, because ice is always less saline than the water from which it is formed; melting of the ice on the contrary will entail a decreased salinity of the surface water of the sea.

From calculation and observation it may be shown that the limiting ice-thickness in the central part of the eastern sector [eastern longitudes] of the Arctic is less than the mean thickness (taking into account hummocks) of the ice in the marginal seas of this sector.

What is more, hummocking is at its maximum when ice-fields are being driven against fast ice or the shore (in these marginal seas). In the Arctic Basin itself Nansen only occasionally sighted a hummock as high as seven meters. The height of the largest hummock surveyed by the Sedov ... on March 24th, 1939, at $86^{\circ}23' \text{ N}$ and 109° E ... was 6.1 meters. In the marginal seas the hummocks reach a much greater height, and they are more frequent than in the Central Arctic. For instance in April 1944 in the Chuckchee Sea off Koliuchin Island the hummocks reached as much as fifteen meters in height. In March 1941, Aircraft N-169, at about 75° N and between 160 and 165° E ., sighted hummock formations which in shape and size were comparable to icebergs.

When such mighty ice formations, built up during the winter in the marginal seas, are carried into the Arctic Basin, they gradually decrease in thickness, the ice melts, and the surface layers of the water under the floes become somewhat less saline.

During the Sadko expedition of 1935 the surface salinity in the northern part of the Kara Sea was less than it was on approximately the 79th parallel between Franz Josef Land and Severnaya Zemlia. In the region of the Pole of Inaccessibility* the salinity of the surface waters gradually decreases as one goes northward from the latitude of Wrangel Island. According to the Station North Pole observations, the salinity of the surface waters is least at the Pole itself, and gradually increases toward the south. Thus in the central part of the Arctic Basin the salinity of the surface waters is not being increased by formation of more ice but on the contrary is being decreased by ice melting; consequently, as I was able to demonstrate, the waters of the Arctic Basin are separated from the fresher coastal waters by a unique zone of water of higher salinity, extending approximately along the continental shelf.

This is one of the phenomena explained by the fact that in the Central Arctic the limiting thickness of ice-formation becomes less.

The Sedov people during their drift devoted much time to ice observations. Besides describing the composition of the floes and their snow-cover, they took measurements every ten days of the thickness of ice formed by natural growth, that is, without any hummocking.

Similar data obtained by the Fram indicated that the thickness of smooth ice-fields, formed by natural freezing and growth, might reach as much as 635 cm. The Sedov drifted farther north than the Fram,** yet the thickness of smooth floes never exceeded 220 cm. This illustrates the fact that at the present time a warming-up of the Arctic is taking place. On this very interesting question I shall have more to say later.

Moreover the Sedov observations again confirmed the following principles:---

(1) The accretion process continues even in summer, because of the low temperatures of winter being held over in the interior of the floes.

(2) A floe which has become saturated with water during summer from the molting of its snow covering takes a long time to cool right through when cold weather sets in, and until then it does not increase in thickness. Thus

* 80°N 175°W approximately. The point for which the summation of distances from surrounding land-masses is a maximum.

** See Frontispiece Map II.

in the region of the Sedov drift the ice did not begin to increase in thickness until about the first half of December, in spite of the fact that the atmospheric temperature had fallen below zero Centigrade by early September. Thus it took about two and one-half months of the autumn for the ice to cool right through.

As I have said, the thickness of palaeocrystic ice depends not only on the number of degree-days of cold, but also on the amount of summer melting.

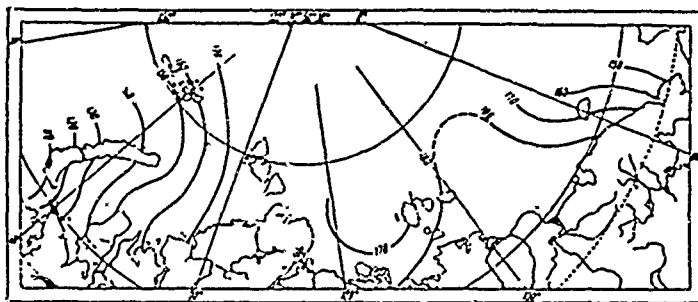
In the region of the Sedov drift, the degree-days of cold per winter amounted to about 6000. What thickness of ice ought there to have been on the Sedov's course, for different amounts of summer melting? Below are given some figures calculated on the basis of a formula derived by myself from the observations of a large number of Arctic stations.

Summer melt (in cm)	Ice of 1936 formation	Ice of 1937 formation	Ice of 1938 formation
10	342	279	196
50	291	253	196
100	241	225	196
150	208	205	196

From this table it is clear that to explain the small thickness of the ice in the region of the Sedov drift we must suppose the summer melt to have been increasing in recent years.

The thickness of the ice field of Station North Pole was three meters. The question naturally arises: where had this ice been formed, and from where had it been carried to the North Pole?

It is immediately apparent that Station North Pole's ice-field must have originally been formed in much more severe regions of the Arctic, where the number of degree-days of cold is somewhat greater and the summer melt considerably less than in the region of the Sedov drift.



Thickness of growth-ice formed in the winter of 1938-39 (in cm).

h. The Ice-Packs

The Eurasian sector of the Arctic differs in many ways from the American sector. For one thing, it is cut up into separate fingers or segments by patches of islands and archipelagoes extending northward far out from the mainland. Bear Island and Spitzbergen divide the Greenland Sea from the Barents Sea; Nova Zemlia and Franz Josef Land divide the Barents Sea from the Kara Sea; Severnaya Zemlia divides the Kara Sea from the Laptev Sea; the Liakhov and New Siberian Islands divide the Laptev Sea from the East Siberian Sea, and Wrangel Island the East Siberian Sea from the Chuckchee Sea.

Though all these seas, as I have said, are really nothing more than bays of the Arctic Basin, there is nevertheless set up in them a circulation of cyclonic nature which is especially well-marked in the winter season. It is caused first of all by the fact that along their southern shores the water warms up more thoroughly, and in the second place by the great volume of runoff from these shores. In the Greenland and Chuckchee Seas, where there is almost no influx of land water, and to some extent in the Barents Sea, a similar rôle is played by the warm waters of the Spitzbergen, North Cape and Pacific Currents flowing in from the south.

As the lighter coastal waters (lighter, because they are warmer or because they are much less saline) flow northward, they are deflected by a force due to the earth's rotation and urged over against the western shores of Spitzbergen, Novaya Zemlia, the Taimyr Peninsula, the Liakhov and New Siberian Islands, and Alaska. On the other hand the surface water and ice of the Arctic Basin are sucked in along the eastern coasts of the said archipelagoes. This simple system may be very much complicated in one region or another by the contours of shore-line and sea-bottom, and likewise by atmospheric circulation; nevertheless its basic features may be traced in all the seas of the eastern sector of Arctic.

Let us imagine that at the height of the Arctic summer (end of August and beginning of September) we make an ice-reconnaissance flight from the coast of Greenland across to Behring Strait. In our course we should see one stretch after another of open water free of ice, alternating with accumulations of 8/10 or 10/10 ice, that is, ice occupying from 80 to 100 percent of the available space. If we repeated this Arctic trip at the same season of the following year, we should see that these accumulations or ice-packs and the open ice-free stretches of sea are located in a general way just about where they were before. From this we might conclude that their distribution is not governed by chance but by some law; that it is indeed completely determined by definite geographic agencies.

We might further notice that some of these ice-packs are like tongues or spurs jutting out from the pack-ice of the Arctic Basin and are being continually replenished by ice from the north. Others are at the end of summer completely cut off from the Arctic pack. They are mainly formed by ice of local origin, in most cases by break-away fast-ice. Packs of the first type are considerably more permanent than those of the second type.

Among the packs of the first type are:-

The Greenland Pack, a tongue of the Arctic ice which descends to the south along the eastern shores of Greenland and then rounds the southern tip of the island into Baffin Strait;

The North-east Barents Sea Pack, which descends, first to the south and then to the southwest along the eastern and south-eastern coast of Franz Josef Land;

The Taimyr Pack, which descends to the south along the eastern shores of Severnaya Zemlia and the Taimyr Peninsula;

The Aion Pack, which descends along the western shores of Wrangel Island to Aion Island and in turn feeds the Chukhotsk Ice-Pack, a tongue of ice extending to the east along the northern shores of the Chukhotsk Peninsula.

These southward-hanging tongues of pack-ice are replenished at the north and consumed by melting at the south. In those years when the amount of melting exceeds the amount of feed-in, the pack as a whole occupies a more northerly position. At times these packs break up into sections; when this happens, each section broken off might be considered as an ice-pack of the second type.

Among the ice-packs of the second type are:-

The Spitzbergen Pack, which is gradually moving south and feeding the Bear Island Tongue which rounds Spitzbergen on the south (the so-called Southern Ice-pack of the Greenland Sea);

The Novaya Zemlia Pack, which extends along the eastern shores of Novaya Zemlia; it consists of local floe-ice and in warm years it disappears completely;

The Severnaya Zemlia Pack, on the south-west coast of Severnaya Zemlia;

The West Taimyr Fast-ice Pack, formed basically from break-away fast ice from the straits between the islands off the coast of Khariton Laptev;

The Yana Pack, which is formed from the fast-ice north of the mouth of the River Yana.

If we look at the distribution of these ice-packs, the first thing which strikes our eye is that local packs build up in stagnant zones, that is, where steady currents are almost non-existent.

Our attention is furthermore drawn to the uniformity of concentration of the ice in these packs. Their area may decrease, halving itself several times over, and the pack as a whole or sections split off from it may move about to a considerable extent, but the concentration of ice remains approximately the same, namely higher than 7/10.

Moreover the fringe of an ice-pack may be either close-packed or straggly. A close-packed fringe is caused by winds driving toward the main body, a straggly fringe by winds driving away. When your ship is approaching the straggly fringe of a pack, you first encounter small cakes of ice broken off from the main body; these increase in number and size (i.e. the coefficient of concentration or ice-coverage increases), until finally you have the large floes and ice-fields which so to speak constitute the real framework of the pack.

This [graduation of sizes] is explained by the fact that ice formations which are small and do not draw much water can get under way faster and drift faster with the wind than the larger masses of deeper draft.

When the wind changes and blows toward the pack, only a portion of the ice which has broken away returns, and what returns is much reduced in size. Most of it has melted in water more thoroughly heated by the sun.

Ice floes disintegrate most rapidly on contact with warm water, and the less concentration of ice there is on the sea the more rapidly the melting proceeds. Thus according to my calculations the melting process will diminish the concentration of the ice-cover from 5/10 to 1/10 in half the time it takes to decrease it from 9/10 to 7/10.

All these facts go to explain why it is that although the ice-packs decrease so much in size during the summer they nevertheless maintain their concentration until they finally break up.

5. Glaciers

In the Arctic regions, and also in some regions of the temperate ocean latitudes, we may encounter ice-masses of glacier origin, distinct in shape and characteristics from marine ice-formations.

On the high mountain ranges of the temperate and equatorial latitudes and more particularly in the Arctic regions, where the summer melt is less than the precipitation each winter, there takes place a steady accumulation of snow in every hollow or depression. Moreover, snow from nearby higher places is carried into these hollows by the wind or by its own weight.

As the blanket of snow becomes gradually heavier the lower layers are packed hard, and through the effects of the pressure, which lowers the freezing point, these layers are slowly transformed. The first step is the formation of firn ice, consisting of separate granules of ice of a white color; then bubble ice is formed from the granules freezing together along with a great quantity of air bubbles. The final step of the transformation produces blue glacier ice.

Glacier ice is sharply distinct in its composition from sea ice. Water obtained from melted glacier ice is practically indistinguishable from distilled water.

Glacier ice consists of irregularly rounded granulations, each of which is a crystal. The granules sometimes reach the size of a pigeon's egg, and the deeper they lie the larger they are. In the Alps, crystals have been found weighing up to 700 grams. It is believed that the growth of these granules is due either to water from melted ice getting into the spaces between the crystals, or to the larger granules absorbing their smaller neighbors. It seems characteristic that every accumulation of ice in time acquires a granular structure, and glacier ice, particularly at the glacier front, is always very ancient.

In addition to its granular structure, glacier ice is characterized by stratification and banding; on the faces of the vertical walls of glaciers and icebergs one may see that the ice-mass is made up of a succession of more or less wavy white and blue strips. Some scientists believe that these strata have something to do with precipitation cycles. This is indicated by the fact that in southern glaciers the different strata are separated one from another by the dust which blows on in summer. Others suppose that the stratification of glacier ice comes about through one layer slipping relatively to the other. At the junctions of these layers blue ice is formed by melting and pressure, while the body of the sliding layer, consisting of firn ice, remains white. A third group of scientists is inclined to admit that both factors play a part in the formation of stratified glacier ice. The peculiarities mentioned allow us to regard glacier ice as pressure-ice, in contrast to thermic ice formed from the sea.

When a hollow place gets filled up with snow and ice, the glacier ice begins to flow out of the region where it has accumulated.

The plasticity of the ice and its ability to flow down valleys is a most notable property of glaciers. The speed of glacier movement is approximately one ten-thousandth that of the speed with which water flows (with the same amount of slope).

When they flow, glaciers, exactly like rivers, detour around isolated high spots, split into branches, and gather tributaries into themselves.

In the tropical and moderate latitudes the basins of snow and ice which feed the glaciers are found in valleys at high altitudes, between the ridges and crests of the mountains. The glaciers flowing out of these basins gradually break up and melt at their lower ends and finally give rise to mountain rivers.

As we come nearer to the pole, the snow-line descends lower and lower, and the glacier fronts begin to dip down to sea level. Here the glaciers form part of the coastline, change the contours of the neighboring sea-bottom, and constitute an inexhaustible source of icebergs ... masses of glacier ice floating in the sea.

In some regions of the Arctic there exist great ice-shields which cover whole islands; in the Antarctic there is a whole continent covered by such an ice-shield. The principal difference between the Arctic and the Antarctic, as we have indicated, is that there is an immense continent at the heart of the latter, while the center of the former is occupied by the deep Arctic basin. The great mass of Arctic ice is sea ice; that of the Antarctic is glacier ice.

The most ice-bound territory in the Arctic is Greenland, in which is concentrated 90% of the glacier ice of the northern hemisphere; it occupies 1,900,000 square kilometers of this island's total area of 2,100,000 square kilometers. The continental ice-sheet of the Antarctic occupies an area of 14,000,000 square kilometers, of which 11,300,000 square kilometers lie over dry land and the remainder in great tongues of ice over the sea. Some of these tongues, 40 kilometers or more wide, stretch 140 kilometers out to sea.

In the northern hemisphere, continental ice-caps or mantles descending to sea level are found on the shores of Baffin Strait as well as in Greenland. Various other ice-caps are found in the American sector of the Arctic on Bylot and Devon Islands, on Axel Heiberg Land, on Ellesmere Land and on Baffin Land. In the Eurasian sector of the Arctic, ice-caps or mantles are found on Spitzbergen, on White Island* and Victoria Island, on Franz Josef Land, on Novaya Zemlia, on Ushakov Island and on Severnaya Zemlia. East of Cape Cheliuskin ice-caps may be seen on Bennett, Henrietta and Jeanette Islands, but it is only on Henrietta Island that some small glaciers reach the sea.

A fact to remember is that 16,000,000 square kilometers of the surface of our globe, that is, about 11% of all the land area, is covered with eternal ice. In the northern hemisphere ice-caps cover 20% of Iceland, 31% of Novaya Zemlia, 42% of Severnaya Zemlia, a little less than 90% of

* See pages 22, 30. (Tr.)

Greenland, 90% of Franz Josef Land, and 100% of White, Victoria, Ushakov and Schmidt Islands.

The ice-sheets of the northern hemisphere are distinguished by the fact that the most northerly land-areas, the northern coasts of Greenland and Ellesmere Land, are free of glaciers. Glaciers are almost non-existent in Labrador too, which has a very low summer temperature (about 7°C) and is moreover situated on the course of summer cyclones. Likewise they are almost non-existent on all the northern coast of Spitzbergen. From this it follows that for glaciers to form it is not enough to have high latitudes and low summer temperatures. Neither is height above sea level enough in itself, nor a large expanse of land. Witness for instance the very small Victoria Island (8 kilometers long), situated between Spitzbergen and Franz Josef Land; it is almost completely covered by the ice, while islands of considerably greater height and greater size on the map, and indeed with a more northerly location (off the northern shores of Spitzbergen for instance) have no ice-cover. To this question I shall return later.

There is no doubt that the most important factor, other things being equal, is the precipitation. It is known for instance that on the drier northern side of Iceland the snow line is found at 1100-1300 meters above sea level, while on the southern side, which has a damper climate, it descends to 600-800 meters, that is, 300-500 meters lower.

Of all the ice-sheets in the northern hemisphere, that which has been most studied is the glacier ice-cap of Greenland. This ice-cap has several different crowns and on the 70th parallel reaches a height of 3150 meters; north of Angmagssalik, Mount Forel rises 3350 meters. In its western part the thickness of the ice is nearly three kilometers. If the whole mass of the Greenland ice were to melt, the level of the oceans of the globe would rise approximately 8 meters and many coastal cities would be submerged. For purposes of comparison I may add that if all the ice covering the Antarctic continent were melted, the ocean level would rise 23 meters. If all the ice on the globe melted, then the World-Ocean would rise 50 meters. It is believed that during the last glacial era the ocean level was at least 100 meters lower than at present.

Between its northern and southern crowns, a little north of the 70th parallel, the Greenland ice-shield is crossed by a deep trough. The ice flows down the slopes of each crown into the trough and then down the trough to the sea, mostly to the Baffin Strait side, because the climate is milder there, and also because the eastern rim of the ice shield is higher than the western. It is the existence of this cross-trough which explains the fact that most of the Greenland icebergs are calved between 65° and 70° north latitude on the western side of this island.

The speed at which some Greenland glaciers crawl along is quite high, for instance the Karayak glacier on the western shore (70°N., 50°W.), which has a maximum width of 5.5 kilometers and an ice-face height above sea level of 100 meters, moves at a speed of 20-25 meters per 24-hour day, almost twenty times the speed of the fastest-moving Alpine glaciers. The Jakobshavn glacier lying a little farther to the south has the same speed

and does not come to rest even in the winter season.

It should be mentioned that the speed of glacier movement depends on climatic conditions. In cold years it slows down, and speeds up in warm years. So too in cold years the glacier fronts advance, while in warm years they retreat from the sea. We get the impression of a gigantic ice-octopus, covering nearly all of Greenland with its cold body, and extending or retracting its huge white tentacles from time to time. At the moment all these icy devil-fishes, large and small (including that of Greenland), are pulling in their tentacles, in consequence of the general re-warming of the Arctic.

I have already pointed out that the continental ice-sheet occupies nearly 90% of the surface of Greenland, but if we take a ship around Greenland we might never notice the fact. At the end of the Arctic summer we see the shores bare of snow; we see either the cliffs which here they call nunataqs or low spits of land.

The same impression is given by Spitzbergen, that island of sharp-peaked mountains. Sailing along the Spitzbergen coast in clear weather, what you see are these mountains. Many of them are strangely like the pyramids of the desert, and they are half sprinkled over with the sand of the Arctic desert ... snow.

Very different is the impression produced by the ice-cap islands.

6. Ice-cap Islands

Glaciers are a natural phenomenon quite to be expected in many high mountainous countries, for here the snow which is needed to form glaciers accumulates in vast feeding-areas.

But the ice-cap islands are a big geographic puzzle. These islands, in spite of their small height above sea level and their small size, are almost entirely buried under ice, which breaks off sharply at the sea's edge to form perpendicular walls of greater or less elevation. The ice-crown, reminiscent of the shell of a tortoise, rises smoothly to the center of the island; which it covers like a cap.

Many of these islands are buried under their ice-cap completely ("completely" in the most literal sense of the word). Among these are Bruce, Raynor and Evaliv Islands in the archipelago of Franz Josef Land; also Ushakov and Schmidt Islands, lying between Franz Josef Land and Severnaya Zemlia. In other cases, only small low-lying spits of land project from under the ice wall. Of this type are White and Victoria Islands, which lie between Spitzbergen and Franz Josef Land.

Aside from these which I enumerate, perhaps no other clear-cut ice-cap islands are to be found in the eastern sector of the Arctic, and all of those mentioned I have had the opportunity to see with my own eyes.

I saw my first ice-cap island in 1930. This was Gillis Land* or, as we now call it, White Island. We anchored off this island in the motor sailing-vessel Knipovich, and later cruised along its southeast shore. In 1935, aboard the auxiliary icebreaker Sadko, we skirted its north-west shore. Thus I have seen this island from all sides. It stretches in a southwest-to-northeast direction, is about 40 kilometers long, and 7 kilometers wide at its broadest part.

The whole island, except for two spits of land at its southwest and northeast extremities, is covered with a solid sheet of ice, rising smoothly to a height of 180-200 meters. At the sea's edge it drops in a steep cliff 20-30 meters high, with its upper rim somewhat overhanging the water. Blocks of ice are continually breaking off this wall. The island is surrounded by small icebergs, aground in shoal water.

In 1930, the same year as above, we took the Knipovich into the Franz Josef archipelago where we circled Bruce Island and anchored off shore. In the case of this island there was not a single patch of ground that I could see. The ice-crown descends smoothly into the sea without a break.

In 1932 we cruised completely around Victoria Island (80°09'N., 36°42'E.), made a landing, and raised the Soviet flag on this most westerly island of the Soviet Arctic.

This island, in spite of its small size (7 x 3 kilometers over all), is completely covered with a mantle of ice rising to 150 meters' height, except for the small spit of land at its northwestern extremity on

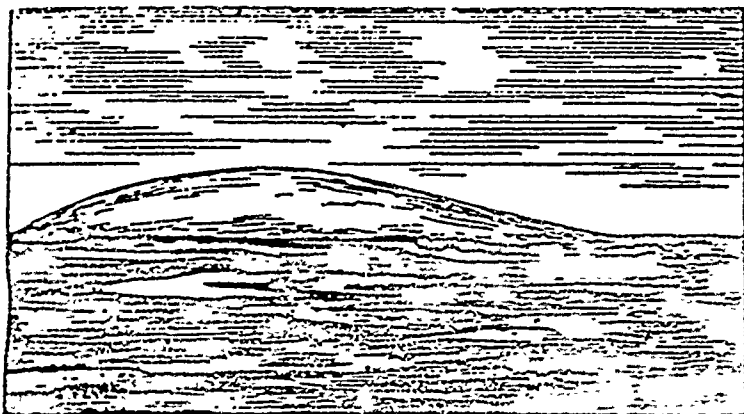
* See pages 28-30. (Tr.)

which we raised the flag. The ice-cap breaks off in a sharp cliff at the sea's edge, just like that on White Island, but not so high. On examining it at closer range, it was seen that the ice-wall of the island was not uniform but consisted of horizontal, slightly wavy strata of different thicknesses. Each of these strata seems to show the climatic conditions existing at the time it was formed. The less the precipitation and the greater the summer heat, the thinner the layer formed during the year in question.

In the same year 1932 and on board the same vessel we skirted Hvidtland, discovered by Nansen in 1895 when he was returning to Franz Josef Land after an unsuccessful attempt to reach the North Pole.

Hvidtland is really a "white land". There is not a point of land showing; just a solid glacier descending to the sea, in some places smoothly, in other places abruptly. Around this island we did not see a single ice-berg.

Nansen reported that Hvidtland consisted of two fair-sized islands, which he called Eva and Liv after his wife and daughter. We however showed that these are really only one island, consisting of two heights of land separated by a trough, thus giving the impression that there are two islands. The impression is strengthened by the fact that along the eastern side of the western height-of-land there are cliff-tops showing through the ice. On my suggestion this reunited island was named Evaliv.



A typical ice-cap island: Ushakov Island
(sketched by V.A.Berezkin).

In 1935, as I have mentioned, we took the auxiliary icebreaker Sadko along the northwest shore of the sea and discovered an ice-cap island which we named Ushakov Island, after our famous explorer of Severnaya Zemlia.*

It is by the way interesting to note the circumstances under which this island was discovered. At the time we were proceeding southward along the western edge of the

Sadko Bank which we had discovered. The weather was foggy and visibility poor. We had been sighting icebergs among the floes through which we were forging ahead. The smooth rounded-off shape of these bergs testified that it was some time since they had broken off from their parent glacier. Indeed some of them, it seemed, had already rolled over; this at least was indicated by their dirtiness on top. Yet as we proceeded to the southeast the icebergs became "younger". They were whiter and their edges were sharp-angled. Our heads buzzed with

* See page 33. (Tr.)

speculation and guesses. One of these guesses, which the evidence gradually strengthened, was that the birthplace of the icebergs was somewhere not far off. We began to search in earnest, and suddenly through the fog an island showed up, which we were approaching from the north. A small party was sent ashore. Later we had a chance to approach Ushakov Island from the south also. Apparently it is entirely covered with ice.

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During the same voyage we circled Schmidt Island, discovered in 1930 by the Sedov, and given this name by the expedition in honor of its leader. Schmidt Island resembles Ushakov Island.

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The ice-cap islands which made the strongest impression on me were White and Evaliv. Possibly this was because I saw them under surprisingly clear weather conditions.

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In the middle latitudes the finest time of the day is considered to be the morning or the evening. To reach us, the sun's rays have to come a longer way through the layers of the atmosphere than at mid-day; hence at morning and evening time they are more brilliantly colored. But the morning and evening in the middle latitudes are short. In the high altitudes however the sun is so low in the sky, even at noon, that the morning or evening type of lighting is all we get. This is the secret of the enchantingly fine Arctic days. In the summer season of the high latitudes there is no full day. There is a long morning which goes over into a long evening.

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I saw Evaliv Island under the noonday sun. White Island I saw at noon and also at midnight under a full moon which never set throughout the 24-hour day.

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Here is an extract from my log book concerning our cruise in the vicinity of White Island in 1930.

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"We are riding at anchor off the cliff-wall of the glacier, on top of which there is a white bear coming towards us down to the edge of the precipice. He comes to the glacier edge and surveys us for a time, then, apparently not finding in us anything to interest him, he lies down for a while in the snow. Then he gets up and goes off up the slope, vanishing in the fog.

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"The wind has gone down completely and the fog is gradually clearing. The full moon illuminates the icebergs which surround us and the glacier-wall off which we are anchored. The snowy cap of the island looks like an inverted bowl of dull silver, sharply etched on the background of the yellowish dawn."

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Later, concerning my daytime impressions when we were skirting the island, it says in my log:-

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"To speak the truth, there are few landmarks on Gillis Island. It is really nothing but a snowy round cheeseloaf; broken off at the sea's edge in a vertical ice-wall 10 to 12 meters high."

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"There is a light west wind blowing. It is a wonderful morning, a little misty and overcast We are turning northward"

"It is getting clear. The whole island visible. Behind it the bright, blue sky. The sun's rays are coming from somewhere and turning 'Gillis' ice-wall into golden crystal"

These island ice-caps differ from ordinary glaciers, which squeeze their way along between banks, mainly in their absolute lack of surface fissures or irregularities and their one unvarying slope, of approximately 2-3 degrees.

A most unpleasant thing about the ice-cap islands is the existence of so-called katabatic winds, that is, strong cascades of air down the cold slopes. Such winds have been observed elsewhere, for instance along the edge of the Antarctic continent. The British Polar Air Route Expedition also noted these winds at its main base in Greenland. At Angmagssalik however, a few miles away from the base, there were only feeble or moderate winds. From this it is supposed that these katabatic winds occur at low levels and soon die out because of friction and admixture. When we were lying off White Island in 1930 we too observed this kind of wind. Down the slopes of the Island, raising a dust of snow and breaking the crests of the waves along shore, there came rushing a wind of storm force. Yet at a distance of two or three miles from the shore the sea was perfectly calm.

The ice-cap islands are usually surrounded by icebergs in various stages of break-up; that is, of various ages.

These islands are notable, first for the fact that they all lie beyond the 80th parallel between Spitzbergen and Severnaya Zemlia; second, they all lie among or not far from islands similar in size, on which there are no great accumulations of ice and snow.

Thus for instance in the northwestern part of the Barents Sea, to the south of the typical ice-cap islands White and Victoria, there lie the King Charles Islands, which have no ice covering to amount to anything; likewise to the northwest there lie Foyn, Brock, Charles XII, and the Seven Islands; to the east lies Alexandra Land, which in its northwestern part is likewise devoid of ice.

Between Ushakov Island (of the ice-cap type) and the northernmost island of Novaya Zemlia lies Vizó Island,* which has no ice-cover. To the west and east of Ushakov Island, the adjacent portions of Franz Josef Land and Severnaya Zemlia are comparatively ice-free.

Hence the question arises: may not the ice-cap islands be relics from the last Ice Age? Hangovers?

In this connection it does not seem very likely to me that Greenland is a single island; it is more probably an archipelago like Spitzbergen. With the general re-warming of the Arctic, the first thing that will happen is that channels will melt out and Greenland will begin to fall apart into separate islands. And of course in this process some of the islands

* Or, Wiese Island. (Tr.).

themselves will in the end free themselves entirely of their mantles of ice.

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This hypothesis perhaps finds additional support in the fact that our present notion of Greenland as an island makes it the largest one on the globe. Its area is about 2,100,000 square kilometers, while the area of the next largest island, New Guinea, amounts to only 800,000 square kilometers.

The great numbers of icebergs which we encounter off the shores of the ice-cap islands, particularly those which stand isolated like White, Victoria, and Ushakov, are furthermore an indirect evidence that these islands are even now in a stage of disintegration. They have a precipitation (on Franz Josef Land it is about 500 millimeters per year in the south and about 300 millimeters in the north) which is insufficient to balance what the ice-cap expends in calving icebergs.

I should point out that glaciers may be fed by more than just the visible forms of precipitation. Clouds made up of strongly over-cooled water-droplets may cross the cold summits and deposit hoar-frost.

The importance of hoar-frost in glacier-feeding is a matter on which very little light has been cast, but it is known that in Swedish Lapland at a height of about 2000 meters, and in the Alps at heights of 2000-3000 meters, a considerable accumulation of this kind of precipitation may form. In the Arctic lands hoar frost may have a quite important part to play, and it may play an even more important part in the case of isolated ice-cap islands. However, it would scarcely be enough to make up the amount of ice expended in calving icebergs.

Finally it is necessary to emphasize that the riddle of the ice-cap islands becomes still more complex if one takes into consideration the following facts:

White Island, the ice-cap of which rises 200 meters above sea level, is situated approximately at $80^{\circ}10'N.$, $33^{\circ}W.$, that is, 120 kilometers north of the King Charles Islands. On these King Charles Islands, which as already stated have practically no ice-mantle, marine terraces have been found at heights of up to 240 meters, heights about the same as that of the White Island crown. This testifies to a general upheaval of the region around White Island.

What is even more surprising, driftwood has been found at heights of up to 45 meters on the King Charles Islands, and of course it could not have been thrown to such a height by the waves. This fact, even more convincingly than the terraces, testifies that the islands have risen, and indeed not so long ago. It is a well-known fact that there are almost no bacteria in the Arctic and things therefore rot very slowly. But we cannot suppose that driftwood would be preserved in the Arctic for great periods of time.

On the other hand, it is well known that deer-horns have been found on Franz Josef's Land, though no one ever saw live deer there. There are deer on Spitzbergen. Thus for instance during the time the Hecla was

lying in Traurenberg Bay, from the 19th of June to the 28th of October 1827, seventy wild deer were killed. We wonder how these deer got to Spitzbergen. May they not have made their way over the ice from Novaya Zemlia via Franz Josef Land, Victoria Island and White Island? Who can yet tell what the answer to this question may be!

Gillis Land

The following is an extract from Chapter IV (not here translated) of Zubov's book which is of interest in connection with the above.

From the history of Arctic voyages we know that in the year 1707 Captain Gillis got to a point roughly 1° north of the tip of Spitzbergen, without encountering ice. Here, a comparatively short distance from the northeastern shore of Spitzbergen, he glimpsed a very high land-mass, to which the name Gillis Land was given. In the next 158 years, that is, from 1707 to 1865, no one devoted any attention to this land-mass, and they were ceasing to show it on maps.

Without going deeply into the history of this matter. I note that on British Admiralty Chart (No.2282) compiled in 1872 and reprinted in 1928 with corrections, there were two Gillis Lands with slightly different spellings. There was a Gilles Land at 80 to 80°10'N and 31 to 32°E, and a Gillis Land at 81°30'N 36°E. The latter was indicated in dotted lines on the chart, and close to it were the words "according to Captain Gillis, 1707 A.D." This shows how confused the question of Gillis Land had become. And all the while this island was not actually being sighted by anyone, although there were many who tried hard to see it. S.O.Makarov thought he saw it on the 14th to 15th of August 1899, when the icebreaker Yermak was at a point 30 or 40 miles to the north-east of the Seven Islands (north of Spitzbergen).*

"Did we really sight land?" writes Makarov in his well-known book "The Yermak in the Ice". "I think we did, but I cannot guarantee it. The fact that the shore which we sighted appeared to be of variable shape indicates that it was at a greater distance from us than the Seven Islands, which according to our reckoning were 30 to 40 miles away. If the distance was greater, then the coast we saw was mountainous, and we must suppose it to have been about 100 miles from us. Hence, judging from the bearings of its extremities, this land-mass would have a length of 60 miles along the meridian."

"If this coast exists, it is not that of Gillis Land, which is 160 miles off in a more southerly direction, and it is not that of Franz Josef Land, 260 miles away. It must be a new land, which no one has ever before sighted, and which is awaiting its explorer."

On September 14th to 15th 1925 the English Captain Worsley, at approximately 80°27'N 30°40'E, may have sighted this land.

"I cannot say for sure" writes Worsley, "whether Gillis Land exists, but on two occasions we observed ... a little to the west of the position shown on the chart ... what looked like land."

On the 19th of September 1928, during the search for the remnants of the Nobile Expedition, the icebreaker Krassin also made an attempt to sight Gillis Land, and set her course for that point where it was shown on British chart No.2282. On this course the Krassin entered light ice at approximately the 30th meridian, and after pushing through it for 15 hours (at 60 miles), had by dead reckoning reached the point where Gillis

Land was shown on the chart. But we sighted no land.

On the 12th of September 1930 we took the motor sailing-vessel Knipovich, first northward along the 33rd meridian to the already-known Gillis Island, and then on to 81°20'N, without encountering ice. As we proceeded, we eagerly scanned the horizon to see if the mythical Gillis Land would appear. Soon we reached the edge of the ice, which compelled us to turn first eastward, then finally southward. Thus we did not sight any land, but the geologist M.V. Klenov, on working over the samples of the sea bottom which we had taken, found that they definitely contained fine gravel, indicative of shoal water or the existence of an island.

In 1931 the Knipovich got as far north as 82°N on the meridian of the western tip of Franz Josef Land, without encountering ice. From that point she turned southwest and, following the edge of the ice, dropped down to Foyn and Brock Islands. Thus she again passed through the locality where the British chart showed Gillis Land, and again she discovered nothing.



The Perseus.

In 1934, on board the Perseus, we were in the area to the east of the Seven Islands. On the 3rd of September we steamed due north to latitude 81°13' and then along the edge of the ice, which led us to Foyn and Brock Islands, from where we proceeded northward. To port there was ice, with an occasional stretch of open water. A light and very cold southeast wind was blowing. There was not a cloud in the sky and visibility was excellent. And again

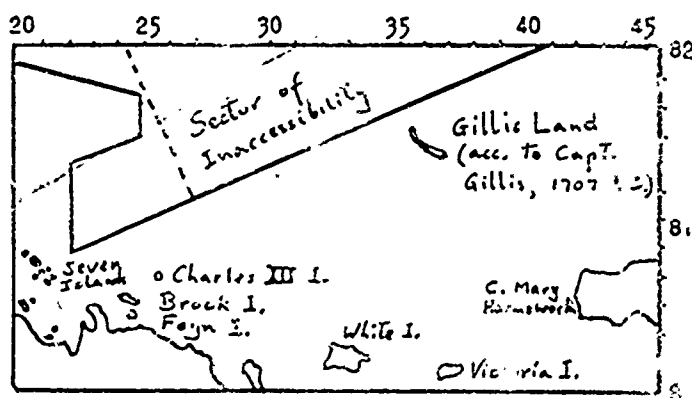
to port, northeast of the Seven Islands, we saw as Makarov did in 1899 the outlines of a far-off, mountainous land. My people made sketches of it. But this was very distant and indistinct. Who can guarantee that it was not the result of refraction, the outlines of far-distant ice hummocks lifted up for us above the horizon?

On the auxiliary icebreaker Sadko in 1935, upon rounding the Seven Islands on the north and battering our way through the ice off the northeastern shores of Spitzbergen, we came out into a large polynia, extending in a north-south direction between latitudes 80 and 81°N. Again the weather was good and the visibility perfect. Just before we got clear of the ice, the horizon began to be obscured by fog. And again we thought we saw signs of land. As soon as the fog came up, there appeared on the horizon northeast of Spitzbergen a characteristic cloud, looking like the misty cap one sees covering glaciers

and snowy mountain-tops when the wind is warmish and damp. At noon he made sketches of the cloud, took its compass bearing and noted the position of the supposed land-mass on the map.

A few days later we once more found ourselves in that same . . . This time we were more persistent, and on the 11th of August we got to northern edge of the polynia. The weather was not nearly so good, but he decided to wait until it cleared, intending to solve the riddle of Gillis Land by using our aircraft. A flight made by Pilot Vaslov was unsuccessful; a dense wall of fog rose where we expected to see land. Another reconnaissance was flown by G.A. Ushakov, the chief of the expedition, and Pilot M.S. Babushkin, but again without success: the same dense wall of fog rose in the northeast right where the land was supposed to be.

Does Gillis Land exist? May it not be that that all these . . . saw was just the result of trying hard to see? Very likely. However, one thing is certain. If we take an up-to-date chart of the area north of Spitzbergen, we perceive that there is some mystery hidden in the region of the hypothetical Gillis Land. All the adjacent region is covered with lines showing the courses of different vessels and expeditions in recent years and it is dotted with the depth soundings which they have made. But if we take a point at latitude $80^{\circ}50'N$ longitude $22^{\circ}E$, and from this point draw a straight line to the northeast, we see that not one ship has ever crossed this line or even come near to it. It is as though this point was the apex of a wedge-shaped sector of inaccessibility extending to the northeast. Moreover on both edges of the sector comparatively shallow depths have been found. Even in years which are exceptionally favorable as far as ice conditions are concerned, the whole of this sector is choked with heavy ice obstructing navigation.

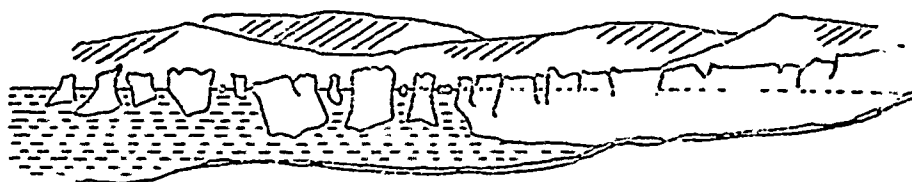


7. Icebergs

The fronts of glaciers which come down to sea-level gradually break in pieces. The glacier, as we say, "calves", producing icebergs of all sizes and shapes.

As a rule, the more rapid the downward movement of the glacier the larger the icebergs it produces. Thus for instance the above-mentioned swiftly moving Jakobshavn glacier has a yield of about 1350 icebergs a year, about 10% of all the Greenland icebergs.

In 1928 it was estimated that there were between 4000 and 6000 icebergs at one time in the long narrow fjord into which the Jakobshavn glacier depends. A remarkable thing is that approximately ten times a year the line breaks through an ice dam which is formed at some point or other; they then drift to the mouth of the fjord, at first slowly but finally with a speed of ten to fifteen kilometers per hour. This movement is accompanied by a terrific noise and continues for some days.



Calving of Icebergs

The Jakobshavn glacier has a total width of 7.5 kilometers and a height of about 90 meters above sea level. It seems to produce the biggest and the most fantastically shaped icebergs in the northern hemisphere. Like most swift-moving glaciers, it has the peculiarity that the icebergs it calves rise higher out of the water than the glacier itself. For instance, icebergs are seen here which tower 140 meters high above the water.

The size of the icebergs depends in part on the speed with which the glacier is moving, but is also affected by the vertical and horizontal dimensions of the glacier. In this respect the icebergs of the northern hemisphere simply cannot compare with those of the Antarctic. The height of the largest Greenland iceberg ever recorded was 149 meters. The East Greenland icebergs are of considerably lesser size: the biggest of them had a height of 70 meters and a length of about one kilometer. The largest iceberg ever recorded to the south of Newfoundland (where almost without exception all the East Greenland icebergs are carried) was 87 meters high and 565 meters long. Yet Antarctic icebergs not infrequently have a length of some tens of kilometers. The exploration vessel "William Scoresby" came across an iceberg in the Antarctic which was about 280 kilometers long and about 20 kilometers broad.

After an iceberg has broken away from the glacier front, it begins to drift about under the influence of winds and currents. Disintegrating gradually and changing its original shape, it is carried out to sea or

stranded in coastal shallows. It is believed that the Arctic icebergs which are carried into the open parts of the Atlantic Ocean seldom have a lifetime of more than two years. Antarctic icebergs, which encounter severer climatic and hydrological conditions on their course, may have a lifetime of ten years and more.

In the Greenland Sea and the Arctic Ocean, icebergs are only of local importance. It is estimated that about 600 small icebergs are calved each year in the Eurasian sector of the Arctic.

In the northern hemisphere the icebergs of Baffin Strait are most important. They are carried out to sea along with the floe-ice by the Labrador current, and cut across the very busy shipping routes between Europe and the principal North American ports. Although the total volume of the Baffin Strait icebergs is only 2 percent of that of all the sea ice formed each winter in those waters, they nevertheless are a serious menace to navigation. Many will remember the loss of the steamship "Titanic" on its first crossing of the Atlantic in April 1912. The Titanic struck an iceberg at 41°16'N 49°46'W and sank; 1513 persons lost their lives.

In the Eurasian sector of the Arctic, icebergs are found in the Barents Sea (mainly in its northwestern part), in the Kara Sea and in the Laptev Sea.

The glaciers of Spitzbergen do not produce any sizeable icebergs to speak of. At least, during our cruise on the Knipovich in 1930 we did not sight a single iceberg from Hope Island to White Island.

On our 1930, 1932, and 1935 voyages we observed many icebergs off White Island, to the south and also to the north. These icebergs were small and vertical-sided. In most cases they had gone aground, clustering apparently on various banks at short distances from the island.

Off Victoria Island, which we circled in 1932, there were few icebergs and they were of small size; for the most part they too were stranded on shoals.

There are more icebergs off Franz Josef Land. They may have a height of up to 25 meters above sea level, and a length of as much as a kilometer. Leigh-Smith mentions one which was some miles long. The ice-cube shape of icebergs is shown most clearly of all in this region. It is possible that this shape has something to do with slow glacier movement. Thus the glaciers on Hooker Island move at a speed of 12-17 centimeters a day; a little more rapidly in summer. One glacier on Rudolf Island showed a speed of 9 centimeters a day during the period April 24th to August 4th, 1933; a stake in the ice moved 9.13 meters in that time. It is interesting to note that at the time of the Count d'Abruzzi expedition (1899-1900) the glaciers on this island had no discernable motion.

In this archipelago icebergs are most numerous off the southwest and northwest shores, if we do not count the straits, where icebergs may be found in the neighborhood of each glacier which comes down to the sea. Here

too it seems they are confined by off-shore banks. At the beginning of August 1928 the Sedov Expedition counted 24 icebergs to the south of Alexandra Land.

Between Victoria Island and Franz Josef Land icebergs are seldom encountered. At least in 1930 we saw only two or three of them, and when we were rounding Franz Josef Land in 1932 we did not see even one, though the visibility was good. At the same time we sighted no icebergs (except in the Straits) on our voyage from Rudolf Island to Hvidtland,* nor further to the south around the eastern coast of Franz Josef Land; neither were there any there on our 1935 voyage.

On the Barents Sea Coast of Novaya Zemlia icebergs are not as a rule encountered at sea, although at the head of practically every fjord of the northern island of Novaya Zemlia there are glaciers which come down to the water's edge.

Thus we must reckon that the greatest producer of icebergs in the Barents Sea is Franz Josef Land. Some years these icebergs make astonishing voyages.

For instance, in April of 1929 a group of icebergs was sighted at 71°N: 34°5'E. In the first ten days of May these icebergs turned up off the Murman Coast.

The bergs had a height of as much as 12 meters above the sea. Later they were swept on by winds and currents into the White Sea funnel, to hang around off the coast of Kenin Land throughout the month of June.

This was a course which icebergs very seldom take. It may be explained by north winds driving them into the North Cape Current, which then carried them along the Murman coast. This instance will also serve to show the longevity of icebergs, a characteristic which is understandable in view of their great and monolithic bulk.

In the Kara Sea along the eastern coast of Novaya Zemlia icebergs are almost not to be seen, the reason being the same as in the case of the west coast: the system of currents and winds in that region drives them to the shore. Furthermore there are shallow bars which will not allow them out of the fjords where they split off from the glaciers.

Many icebergs are encountered off Ushakov Island. In fact, as we have seen, it was just because we unexpectedly met with icebergs that we discovered this island in the fog.

According to observations of the Ushakov Expedition (1930-1932), the ice-sheet reaches its greatest proportions on Komsomolets Island, the northern island of Novaya Zemlia. Here there are several ice-shields from which glaciers descend into Red Army Strait. From this strait icebergs are carried by the winds and currents into the Kara Sea and to a still greater extent into the Laptev Sea. Off the northwest coast of Severnaya Zemlia icebergs are, it seems, seldom met. At least we saw none during our 1935 voyage

* See page 23. (Tr.)

on the Sadko. Off the southwest coast of Severnaya Zemlia icebergs are encountered, coming mainly from Shokal'ski Strait.

In the Laptev Sea off Red Army Strait, the Sibiriakov counted 129 icebergs stranded there on shoals; apparently they had come from the said Strait. From observational records we note the curious fact that since 1932 icebergs have been very rarely encountered in the region south of the eightieth parallel (with the exception of Shokal'ski Strait). Only in 1935 did the Yermak, on her course from Vil'kitzki Strait to Cape Lavrov, count 30 to 35 icebergs.

Beginning in 1939 an increase has been noted in the number of icebergs around Bol'shevik Island, to the west thereof, and in Vil'kitzki Strait. In 1939 these icebergs were mainly seen on the western and southern sides, while in 1940 they were also seen on the eastern side. In this latter year, 1940, a great number of bergs was noticed on the course from Vil'kitzki Strait to Tiksi Bight as far north as latitude 75° approximately.

The indications are that in 1935-1940, in the regions to the west and southeast of Severnaya Zemlia, there was an iceberg maximum, an outbreak similar to that noted off the Murman Coast in 1929.

It is supposed that the bergs which showed up in 1940 off the eastern coast of Bol'shevik Island (in 1939 there were none) came from Red Army Strait, in which they were particularly numerous. There it may be that they accumulate for several years, locked in the fast ice which does not break up, until finally when there are exceptionally favorable weather conditions they may be carried out to sea in great numbers all at once, just as is the case with some of the glaciers of northwestern Greenland. One indication that such favorable weather conditions did in fact exist is the positive anomaly of atmospheric temperatures observed in 1938 and 1939 at Cape Cheliuskin.

The well-known polar flier Padalka informed me that, during a flight on the 27th March 1943 northward of Franz Josef Land on the meridian of Rudolf Island between 84° and 84°30'N, hundreds of icebergs were to be seen, their number decreasing to the west of his course. Yet on the numerous flights made at the same season by Soviet aircraft in connection with the establishment of Station North Pole and approximately on the same course as the above-mentioned, not a single iceberg was seen. Padalka supposes that his bergs came from Severnaya Zemlia. Calculations made by Karelin, according to my method of estimating the drift of ice along isobaric lines, have confirmed Padalka's surmise.

No less striking is the following fact. In October 1943, three kilometers to the north-north-west of Cape Cheliuskin, a flat-topped iceberg was discovered, 1500 meters long, 400 meters wide and rising 10 meters high out of the sea. As the fliers informed me, they sighted this unusual ice-mesa off the eastern coast of Severnaya Zemlia during reconnaissance flights.

What is still more surprising, in 1946 some icebergs were discovered off the eastern coast of Wrangel Island, aground in shoal water, and

in 1947 some were found off the western coast of this island. Until then, no one had ever seen icebergs off Wrangel Island. Calculations which we have made give fairly good indications that these bergs came from a glacier in northwestern Greenland.

Icebergs always interest seamen, if only for the great variety of shapes which they assume and their fantastic coloration under different conditions of illumination. It is an unforgettable picture, a glacier lit up by the sun's rays and descending to the edge of the water, where it is fringed with broken-off icebergs floating in the sea and stranded on neighboring shoals.

But it is not only a question of beauty. Icebergs, swept along at the mercy of the winds and more particularly by ocean currents, go aground on shoals at some distances from the shore and indicate the position of these shoals. Their diversity of shape permits individual icebergs to be recognized over long periods of time and thus by studying the course of icebergs it is possible to learn the direction and speed of ocean currents.

In this field little has been done so far, even in such regions as that of Newfoundland, where an International Ice Patrol has been working continuously since 1914.

However, a most interesting subject for study is the iceberg outbreaks or maxima which are noted both in the northern and in the southern hemispheres.

Thus in the Newfoundland region the years of iceberg maxima (maximum number of icebergs coming south of 48°N, that is, south of the latitude of Stalingrad approximately) were 1890, 1909, 1912 and especially 1929. In the Barents Sea, as we have already noted, there was a typical iceberg maximum in 1929; in the Laptev Sea outbreaks occurred in 1939 and 1940, and so forth. In the Antarctic a great increase in the number of icebergs was noted from 1892 to 1897 inclusive.

What were the reasons for these outbreaks? Whence came the hundreds of icebergs in 1943 in the region northward of Franz Josef Land? Whence came the icebergs off the shores of Wrangel Island in 1946? All these questions are far from being solved and demand systematic and continuous observations. In this field, special air reconnaissance will be called upon to play a great part.

8. Permafrost and Fossil Ice

To the east of Cape Cheliuskin there are no large-size glaciers coming down to sea-level, and the climate here is considerably more severe than to the west of Cape Cheliuskin. In Yakutia, we remember, the Siberian "cold pole" is located; but because of the insufficient snow-fall there are no glaciers in these regions and the ground is locked fast by eternal frost (permafrost).

Suppose that somewhere in eastern Siberia at the end of a hot summer we begin to dig a well. At first the shovel goes into the soil easily, but at a depth of one to two meters we strike very hard ground, frozen right through; it consists of particles of soil mingled with crystals of ice. Still deeper however we reach unfrozen strata of soil, through which underground waters are freely flowing. The stratum of ground which is frozen completely through and which does not thaw out, even in the hot summer, is called the permafrost.

Here the ground always freezes in winter, and the more intense the cold and the less snow-cover there is, the deeper it freezes. We know that snow and ice are very poor conductors of heat: some northern tribes pass even the severest winters in huts built of snow, the so-called igloos. In the winter season snow protects the soil from freezing. Around Leningrad for instance ground denuded of snow freezes to a depth of more than 1.5 meters.

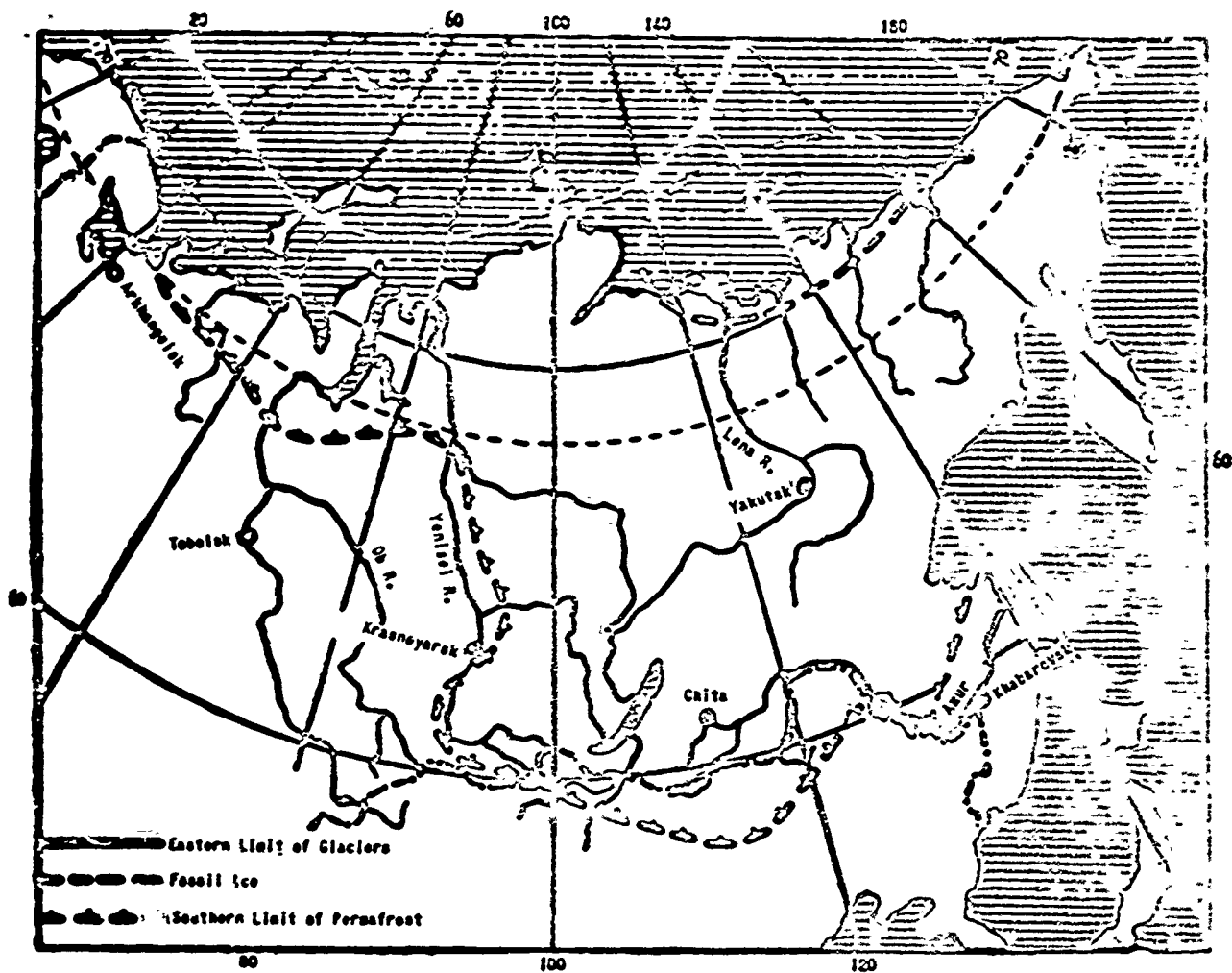
With the beginning of summer the frozen soil thaws out on top. If the winter has not been severe and if the summer is long and hot, then all traces of the winter freezing of the ground disappear, but when a cold summer follows a cold winter a frozen layer may remain over until the next winter.

During that winter the top layer of soil once more freezes; its lower boundary is pushed still deeper. This goes on until such time as there is established a thermal equilibrium characteristic of the locality; the amount of cooling from above is just equal to the amount of heat received from below, from the internal heat of the earth.

In Siberia, permafrost extends over an area of about 9,000,000 square kilometers. The farther north, the thicker the layer of permafrost. Thus on the slopes of the Yablonoi Range the thickness of the permafrost layer varies from three to eight meters; at Irkutsk it reaches 25 meters, and in Yakutia the lower boundary of the permafrost descends to 80-190 meters.

For the lower boundary of the permafrost layer to penetrate down to the line of thermal equilibrium, it takes hundreds and thousands of years. The upper boundary however may alter within a few years' time. Thus for instance there was the case of a deep railway fill built on top of permafrost ground. Twenty years later, it was seen that inside this fill the permafrost level had risen 13 meters; it was somewhat higher on the north side of the fill than on the south.

The formation of permafrost is determined by two factors:— severe winter conditions and scanty snow-cover to protect the ground from freezing.



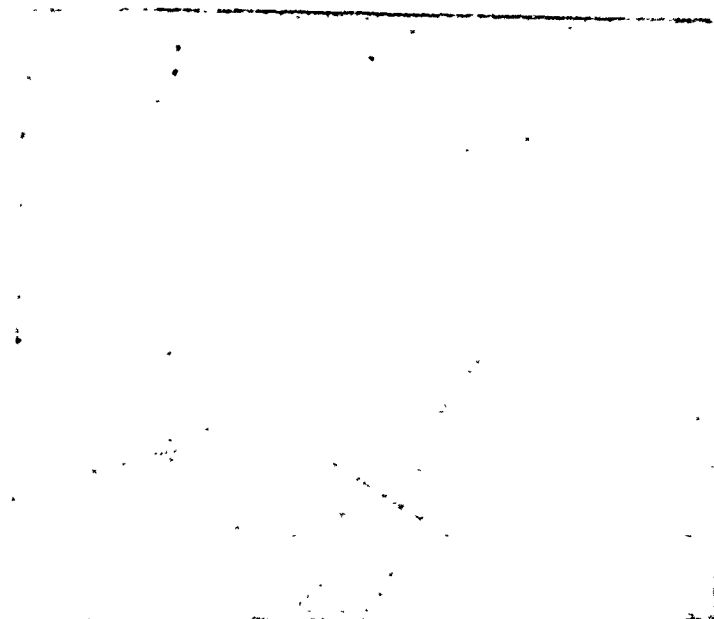
LIMITS OF GLACIERS, FOSSIL ICE AND PERMAFROST

These two causes really reduce to one; namely high atmospheric pressures in the winter season, which mean clear, cold weather.

Permafrost shows almost no effect on agriculture. In Yakutsk for instance, where thanks to the hot summer the soil thaws out to a depth of a meter or more, the inhabitants engage in vegetable gardening and grain-growing.

But in the construction of industrial structures or communal buildings permafrost presents serious difficulties. The top layer of soil which thaws out in summer gets very moist. When the winter cold comes, this layer begins to freeze, and enormous mechanical pressures are built up in it. Materials simply do not exist which are capable of withstanding the terrific pressure of ice-formation, caused by the increase in volume. Huge granite cliffs crumble when water freezes in their crevices. With the onset of winter in places like these, the foundations of buildings and bridges give way, posts and piers break or are pushed out of place; the ground buckles up here and there

in characteristic humps. These humps of ice, which are sometimes as thick as two meters, are called frost-heaves. They are a particular menace to industrial structures. Things are even more complicated when we come to heated buildings, beneath which the permafrost may thaw. The foundation often settles and the buildings are warped out of plumb.



Ice humps.

Permafrost is not always a nuisance. For instance, shafts sunk in permafrost do not need such stout reinforcing as those in more southerly regions: they are not threatened by sudden irruptions of soil water.

In recent years it has been noticed that the southern permafrost boundary is steadily retreating northward. Thus in 1837 at the city of Mezen' wells had to be dug through permafrost. In 1933 you had to go 40 kilometers north to discover traces of permafrost. This retreat of the permafrost is due to a general change in the climate and in particular the general re-warming of the Arctic to which I have already alluded.

It has long been known that at low temperatures many organisms suspend their normal vital activities. This phenomenon is called anabiosis. Experiments have shown that upon return to normal conditions the dessicated and frozen seeds and spores of plants and also the resting-forms of the lower animal orders are still viable. Bacteria also possess the ability to stand

long periods of low temperature. Thus in 1931 bacteria from the fossil ice of Liakhov Island were revived. The age of these bacteria was, whatever the exact circumstances, at least some thousands of years.

Full-grown individuals of the major animal and plant species die when ice crystals are formed in their cells. Possibly death is caused by the rupture of the tissues through the increase in volume of the water freezing in them.

It is well-known that under Arctic conditions many animals withstand very low temperatures. Nadhorst found a microscopic round-worm in the Spitzbergen ice-sheet and revived it by mixing the dried-out slime with water. In Arctic lakes frozen to the very bottom there are living creatures which go into the anabiotic state in winter and revive when summer comes.

On Franz Josef Land, small phosphorescent crustaceans were observed bestirring themselves vigorously in a slush of snow soaked with sea water, the temperature of which was -10°C .

On recently formed sea ice in the Laptev Sea, at approximately 76°N , the Toll' Expedition saw a surprising sight: footprints shone with a faint glow of light dotted with small brighter points; with a stick it was possible to draw glowing lines or letters. The explanation is that the phosphorescent marine organisms or bacteria in sea water were still able to shine even after being caught in solidifying ice.

In the permafrost region we may find earth-worms, tritons and even Siberian marmots spending the winter in ground frozen to a depth of 60 meters. Perhaps the reason why this is possible is the fact that in permafrost we do not find temperatures below -1°C . This is a temperature low enough to freeze fresh water, but it is insufficient to freeze the blood or vital juices of animals, which like salt solutions ice up only at temperatures lower than this.

These facts gave P.N. Kapterev, one of the workers on the Scientific Research Station at Skovorodino ($63^{\circ}53'\text{N}$: $120^{\circ}57'\text{E}$) an idea: might there not be preserved in permafrost the resting-forms of certain organisms which had adapted themselves particularly well to a protracted state of suspended animation?

At Skovorodino the ground at the end of summer is thawed out to 2.5 meters depth, while the lower boundary of the permafrost goes down to about 60 meters.

In 1934 soil samples were taken from the layer at 3.5 meters depth, which contained darker traces of vegetation. These samples were moistened with distilled water and placed in a jar. In a fortnight there appeared algae of the lower types; some of which were unicellular, others confervoid. All these marine growths (and there were 12 different kinds of them) belonged to the green, blue-green, and diatom groups. A little later there appeared in the jar small motile globules of 0.3 mm size. These were crustaceans, *chydorus sphericus*. Some months later, from the same soil in the same jar, the green pedicles of bryophyta began to spring forth. Kapterev states that

the age of the organisms which he revived was, at a cautious estimate, from one thousand to three thousand years. Whether it will be possible to revive animals or animal and plant organisms from the deeper permafrost layers, the future will show.

Once upon a time in Europe and Asia, from the Pyrenees to Alaska and from the Taimyr to the Arals; and in North America down as far as the central United States, there dwelt huge animals, relatives of our present-day elephants ... the mammoths. Their tusks were as much as 7 meters in length, 30 centimeters through, and weighed as much as 70 kilograms. These mammoths likely lived at the same time as the most ancient humans of the Stone Age. A prehistoric picture of a mammoth has been found in a cave, carved on a tusk of one of these very animals.

Since early times men have been finding the huge bones and tusks of these creatures in the Siberian permafrost. In 1799 the Evenki* Shumakov was proceeding by boat along the Lena River in search of mammoth tusks. At a certain place, between the blocks of ice, he spotted a large bulk of some kind, but was not able to make out exactly what it was. The following year he noticed that this bulky object was emerging more clearly. The third year, the animal's flank and one of its tusks was showing. The fifth year, it was completely free from the ice and had rolled down the slope onto the sand of the river bank. It was the perfectly preserved body of a mammoth. Shumakov sawed off both tusks, but abandoned the carcass. The local inhabitants cut meat from it for dog food. White bears and polar foxes also fed off the meat. Two years later the skeleton remained, with part of the skin, hair and flesh. The skeleton is now in the Museum of the Academy of Sciences of the U.S.S.R.

In 1846, there was an astonishingly hot and rainy summer. The Russian engineer Benkendorf was sailing a launch down the flooded Indigirka River, and tells us:

"We caught sight of some black, terrifying, gigantic bulk emerging from the water. We saw a colossal head with huge tusks and a long trunk. The trunk was moving in an incredible fashion, as though seeking something. I could discern the whites of the half-open eyes"

Through the united efforts of 50 men and some horses, the body of the mammoth was hauled up on the beach. It was a splendid specimen of large size, 4 meters high, 5 meters long, its body covered with a thick fleece of yellowish-brown color; it had tusks 3 meters in length, and a thick, two-meter-long trunk. The animal was well fed. In its stomach, in a perfect state of preservation, there were young shoots of spruce and pine and a number chewed-up young spruce-cones. Death had struck the animal down in the flower of its strength. Apparently it had bogged down in a swamp-hole in just the attitude in which it was found (standing on its feet), and then froze. In this attitude it also thawed out. They did not succeed in preserving this specimen: it was carried away by the raging flood of the river.

* Evenki ... a Tungus people.(Tr.)

In 1901, the almost whole body of a young mammoth was found in the permafrost near Sredne-Kolymsk and shipped to Petersburg. This was a male, with one small tusk: the other tusk had been hacked off by someone. The trunk and skin of the head had been partially eaten away by animals. The fleece had come off and was lying underneath the body. The flesh was soft, looking like boiled meat; the dogs ate it greedily. This mammoth is also in the Zoölogical Museum of the Academy of Sciences.

Permafrost, as we have seen, is frozen soil. It is of course to be expected that in permafrost we should find the odd block of pure, solid ice. But in some regions these blocks are so numerous and of such size that they have been given a special name, fossil ice.

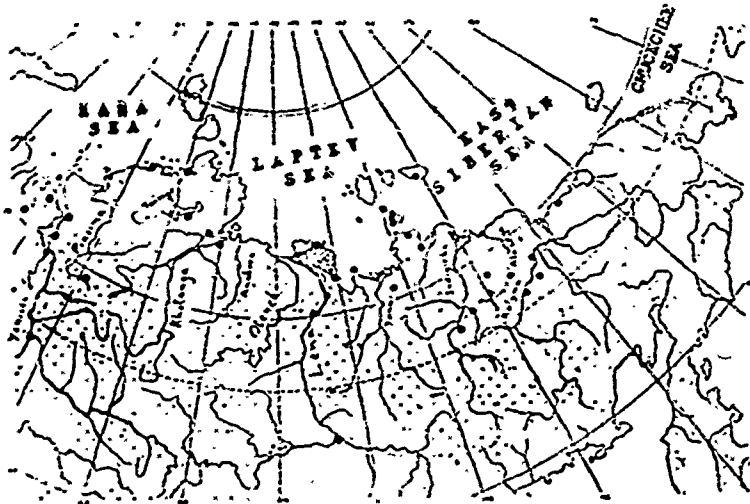
In the Soviet sector of the Arctic, fossil ice is found in the southern part of the northernmost island of Novaya Zemlia and on the banks of the Lena, but in its best-developed form it is found on the Liakhov Islands in the Laptev Sea. On Greater Liakhov Island, 80 percent of the surface of which consists of fossil ice with a top cover of soil, the perpendicular walls of these ice-masses rise 35-40 meters above sea level, while the total thickness of the stratum is as much as 70 meters. In the lower part of the vertical ice-wall of the shoreline the sea has washed out caves and grottos, and cave-ins are continually taking place. Where the shoreline consists of cliffs of this kind, they jut out on the bottom of the sea to form an icy bottom extending far from shore and covered with a silt of material from the land.

Fossil ice-masses are relics of just such a continental ice-sheet as the Greenland ice-cap, and are made up of separate granules solidly frozen together in an irregular structure. The surface of the separate granules is covered with indentations, into which the projections of neighboring granules fit as though mortised and jointed. Thus the structure of fossil ice tells us that it was formed from snow. It is moreover worth noting that in fossil ice too we find the remains of ancient animals; it was indeed on Great Liakhov Island that the last reported mammoth find was made in 1906.

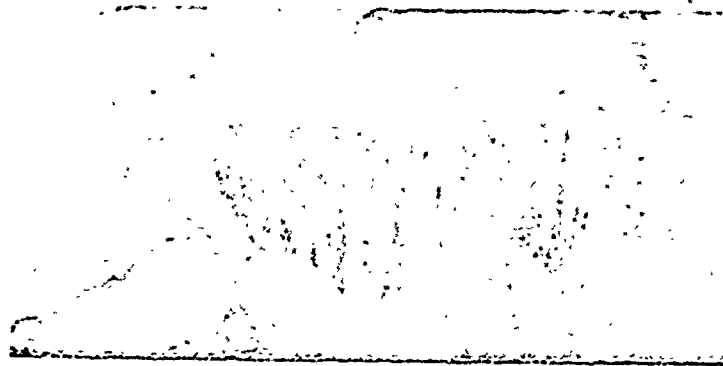
Every year in spring the waters thaw out ever new layers of the fossil ice and bring to the surface ever more relics of the pre-glacial epoch: remains of mammoths and remains of vegetation, testifying that the climate of the pre-glacial period was very much milder than it is now. Toll' for instance in 1893 found whole alder-trees five meters tall on the Liakhov Islands; some of them were so perfectly preserved that the leaves were still firmly set on the branches along with whole clusters of catkins; the bark on the branches and trunk was intact; and so forth.

The Liakhov Islands are a real museum of the glacial epoch. One scientific expedition after another has made its way thither. Nobody can say how many precious, perfectly preserved specimens from times long gone by are yet stored up for us in the fossil ice. It may be that here we shall find not only the complete bodies of mammoths, but also man ... the contemporary of the mammoth.

Russian scientists have been toying with an idea: why not store in the ice the things we find today in our natural environment, for the benefit of our descendants who will be living thousands of years after us? Many forms



Sites [marked by black dots] of mammoth finds.



Mammoth in the ice.



Wall of fossil ice on Great Liakhov Island.

of animal and plant life have become completely extinct or have strongly modified their type. Already we deem it proper to set aside Reservations and Preserves, in order to safeguard the most interesting and valuable species. Such steps for instance have been taken in connection with the bison, the white bear, and even the Ussuri tiger.

How grateful the people of coming millenia might be if they could see preserved intact in permafrost all the things with which nature has surrounded us, their ancestors!

9. Ice and Ice Life

The intensive development of life at the edge of the ice during the period when the seas are freeing themselves of their winter cover is a phenomenon which was long ago noticed. In the water which washes the edge of the melting ice-formations one may observe, during the Arctic summer, an abundant efflorescence of phytoplankton. This abundance of phytoplankton in turn causes an intensive growth of zoöplankton. The supply of phytoplankton and zoöplankton attracts fish and mammals to the edge of the ice. Large numbers of birds come to feed on the plankton or small fish and to rest on the ice. Polar bears hunt walrus and seal at the edge of the floes. Thus is completed a chain of living organisms connected in one way or another with the sea ice.

Several hypotheses have been formulated to explain the efflorescence of life around the melting ice. One of these hypotheses is based on the particular properties and structure of the molecules of water and ice. I have already mentioned that water molecules have been found by some research workers to be rather inert chemically, while ice molecules on the contrary show a greater activity.

I hold the opinion that the outburst of organic life developing around the melting floes may be explained on the basis of an accumulation of various nutritive substances on and within the ice during the whole winter; these substances are suddenly liberated in the thaw, and, one could say, serve as fertilizer for the surrounding water.

Along with the dissolved nutritive substances, various kinds of minute organisms and bacteria freeze up in the ice. Some of them perish from the effects of low temperature, but others survive and develop when the thaw begins, especially bacteria and spores, which will stand very low sub-zero temperatures. These organisms are the beginning of the chain of ice-life, both on the floes themselves and in the water.

I have already spoken of the fact that some organisms are capable of accustoming themselves to very low temperatures.

During the Sadko Expedition in 1935 careful bacteriological research was done on the Arctic ice, on the fresh water lakes which form on the ice during the Arctic summer, and also on the waters of the Greenland, Barents and Kara Seas. In one of the summer pools on the ice a concentration of 60,000 bacteria per cubic centimeter was found, while the maximum bacteria count found by the same expedition in the water of the Greenland, Barents and Kara Seas was only 27,000 per cubic centimeter.

For life to develop around the ice and under the ice it is above all necessary that phytoplankton should develop; this is the fountainhead of nutrition in the Arctic. However for phytoplankton to develop, not only food substances are required, but also sunlight. Continuous floes such as we find in the Arctic do not allow light to penetrate, particularly when they are covered over by a top layer of snow. For this reason we used to believe

that in the Central Arctic there was generally speaking no life under the ice; if any existed, it was only in the pools of snow-water which cover the ice fields during the Arctic summer, or in the open water between the floes. This hypothesis was perhaps sustained by the observations of Nansen which at the time were the only ones available relative to the central portion of the Arctic. Nansen presented the results of his researches as follows:-

"The Arctic Basin, covered in its interior by an almost solid sheet of thick ice, is extremely poor in plant or animal organisms. The sun's rays are absorbed by the ice, and radiation essential for plant organisms scarcely penetrates through the ice fields to the cold waters lying beneath. Thus plant life develops very poorly here during the short summer season (mostly in the polynias between the fields). And without plant life animal life cannot exist. This inner region of the Arctic Basin, continually covered with ice, may be considered a desert in the ocean; neither animal nor man can find sufficient food there. During our expedition on the Fram we found many types of animal life, particularly the small crustaceans, but the fauna was so sparse that our plankton nets could be hung over the side for whole days with only a very small catch to be found in them when we brought them aboard, even though we were drifting at a good speed."

Nevertheless the Fram on her drift sighted whales, both the first summer and the second.

Nansen during his explorations saw signs of the polar bear at latitude 84° in the region to the north of Franz Josef Land. Peary noticed similar signs at latitude 86° in the region north of Greenland. None of the explorers seeking the Pole made any mention of birds or seals. Thus it is all the more surprising that the crew of Station North Pole in 1937 observed a number of birds at the very Pole itself. Apparently these birds were finding sufficient food in the polynias between the floes. Still more surprising was the appearance near the Pole, at 88° North Latitude in the month of July, of a white she-bear with cubs; a sea-hare also showed itself in one of the polynias beside the ice-field. These facts testify that the statements of Nansen and other explorers as to the complete absence of life in the Central Arctic need radical revision.

The Station North Pole researches throw a flood of light on the status of organic life in the region of the Pole. It was found that throughout the whole of August, when the ice field was between 87° and 88° North Latitude, there was a flourishing development of microscopic sea-plants in the upper layers of the water, and there was the same efflorescence of plankton as is observed in spring in the seas of lower latitudes.

This efflorescence begins with the end of the summer, after the melting of all the snow which overlies the Central Arctic ice fields and prevents light from penetrating into their depths, and after the thickness of the ice fields, a factor preventing light-penetration, has somewhat diminished. If then the development of phytoplankton is possible under Arctic conditions, why should the existence of other forms of life be impossible?

In the plankton collected at the North Pole we find forms characteristic of the Greenland Sea. Some of the hauls were difficult to

distinguish from those taken by the Sadko Expedition of 1935 from the Atlantic waters which wash the shores of Spitzbergen. This by the way is still another indication (a biological indication this time) that Atlantic waters from the Greenland Sea do penetrate far to the north, right to the Pole itself.

According to observations made by the Sedov expedition in the summer of 1938, seal were to be seen ~~every day~~ every day in the area where the ship was drifting. Narwhal were particularly numerous. As for birds, gulls predominated but sometimes sandpipers were seen. In the summer of 1939 the Sedov party saw no marine animal life at all. This however may be explained by the fact that there were no rifts nor open water in the vicinity of the ship. On the other hand polar bears sometimes came near to the ship. In the summer, small birds showed up in the drift region from time to time. Their appearance either coincided with or followed strong winds. This gives us grounds for supposing that they were carried there by the wind.

Besides the plankton which develops at the edge of the melting ice floes and in the water under the ~~ices~~ ice, there are very interesting ice-surface organisms which develop with the beginning of summer both on sea ice and on glaciers.

So far, very little is known about the biology of this group of organisms. Usually they are of different colors and impart a tint to the snow and ice. A yellow or dark-yellow coloration is the most usual for ice-organisms and is explained by the fact that these colors will capture the greatest amount of heat. One also finds organisms of green, red and even black coloration. Thus for instance some water-plants cause the phenomenon of pink-snow; others, that of green-snow. These organisms are sometimes so strongly colored and so densely concentrated that they may deceive you. I myself once came upon a patch on the ice of such bright color that I thought "Here's where a polar-bear dined on a seal." On closer examination it turned out to be only a concentration of water-plants. Shirshov* observed pink-snow on the 30th of June at 83°32' North latitude.

In addition to the ice-surface forms of life, there are also characteristic species which develop in the lakes of melt-water; they bear the name ice-plankton. Here the diatoms hold the first place ... tiny sea-plants with a fretwork skeleton of silica.

As a rule, living diatoms are not found on the surface of the ice. They develop only at the bottom of the melt-water ponds, where they form accumulations like dark-colored clots of slime. As already stated, these accumulations absorb a great quantity of solar heat and help in melting the ice. They thaw out pits beneath them, which are usually two or three times greater in width than the clot itself but have the same outline. During the course of the summer the diatoms gradually sink lower and lower into the pits which they hollow out; in the southern parts of the Arctic Basin they finally bore right through the ice and drop into the sea.

In some regions the accumulation of diatoms reaches such proportions that the ice surface over wide areas looks dirty and pitted like a moulder's ladle. Thus there is no doubt that micro-organisms play a definite part in the

* See page 58. (Tr.)

disintegration of the ice floes in summer.

It is necessary to emphasize however that the great numbers of tiny organisms and particles of inorganic origin which get into the ice-floes do not originate from the sea or river waters alone, nor from bottom sediments. As already noted, dust from the land is carried far out to sea by the wind.

In 1946 the most convincing evidence was secured that in this connection the part played by the wind could be of importance.

The ice-breaker North Pole, steaming in the East Siberian Sea 200 to 300 km from Cape Shelagski in the middle of August, discovered live leaf-roller butterflies on the ice. These butterflies were resting on a floe at distances of 5 or 10 m one from the other, their dark grey color standing out against the background of the ice. When alarmed, they took to the air, and when brought on board ship, they flew all over the laboratory.

In the East Siberian Sea strong, warm southerly winds prevailed at that time, and although the ice-surface temperature was fluctuating in the neighborhood of 1.5° to 2.1°C, at a height of 300 m it was between 11.0 and 11.3°C. Let us add that the leaf-roller butterfly is characteristic of the pine woods and deciduous forests which lie far south of the Chuckchee Sea coast. It is evident that these insects were carried by the winds to the ice of the East Siberian Sea.

Everywhere in the World-Ocean the continental shallows (particularly where the depths are of the order of 80 to 100 m) are swarming with life. Thus for instance every spring huge shoals of fish come into our Barents Sea by way of the branching North Cape current; cod, haddock, etc. And every fall these shoals of fish swim out of the Barents Sea again.

Suppose your ship has stopped and is rolling in the swell, let us say somewhere in the North Cape region. You stand at the rail and drop a stout hook, with a sinker but no bait, into the water on a line 200 to 300 meters long. You move the line up and down a distance of about your arm's length. Suddenly the line tightens. You carefully pull it in and haul out a cod of some kilograms weight, which the hook has gaffed sometimes by the gills, sometimes in the belly, sometimes even through the tail. This kind of fishing is called swindling.

What numbers of fish must be there, deep down in the water, if you can pile up a whole mountain of them around you in a few hours of "swindling", and if special trawls will bring in one or two tons of fish, or even more, in half an hour!

Your ship continues on her course to another part of the sea, or returns to the same place after a short interval of time. With impatience you unreel your line ... but not a fish! Put out a trawl, and it too comes in empty.

Question after question arises: what brings our fish to us in the Barents Sea? Why do trawls sometimes come up empty, sometimes with a catch?

We cut open a cod-fish caught in spring off the Murman Coast. The fish is played out, its stomach is empty, and there is no oil in the liver. We cut open a cod-fish caught in the fall in the shallow depths of the southeastern part of the Barents Sea. Its stomach is full and its liver is oily. From this we may draw a simple but very important conclusion: when the fish which we use for food come to us in the Barents Sea in immense shoals, which (as research has shown) are often many hundreds of thousands strong, they come to feed.

Research has also shown that the fish feed over certain definite areas of the sea-bottom, called feeding grounds or fishing banks. On such banks the waters near the bottom are saturated with oxygen and nutritive substances; that is where you find the most flourishing development of the animal life which is the food supply of many of the fish useful to mankind:

These favorable conditions are created by a ceaseless agitation of the bottom waters by currents, by wave motion, and by the vertical circulation due to the fact that the upper layers of the water become cooler and more saline* and hence heavier than the water below. The strongest vertical circulation occurs in the winter season.

In winter, as a result of the vertical circulation, the temperature of the bottom waters on the shallows of the Barents Sea usually drops below -1°C , and in summer this low temperature only gradually disappears, either by direct warming and mixing of the water, or by the cold water being washed away from below and from the sides by warmer waters flowing around the shoals.

It is surprising how sensitive some fish are to temperature conditions. The cod seems to be most comfortable at a temperature of 2 to 4°C ; at a temperature of -1° it freezes.

But this latter temperature, which is fatal to the cod, is nevertheless a temperature at which there is good aeration of the bottom waters and a flourishing growth of organic life.

Accumulations of organic matter are preserved over the winter without decay in this cold water, as though in a refrigerator, and at the very beginning of spring the cod hasten to their immemorial feeding grounds, alternately, repelled by the shock of the cold water and attracted by the wealth and variety of food.

Nowhere else on earth does a shallow continental shelf extend so far out from the coast as in the seas of the Arctic Basin, the Kara, Laptev, East Siberian and Chuckchee Seas. And of course in the northwestern regions of the Barents Sea we often find submarine shoals with depths approximately equal to those of the fishing banks. Yet here there are no fish for us to catch; the bottom-water fauna is not well developed in these areas.

There are certain facts which explain this. In the first place, the water in these regions is covered over for too many months of the year with

* Through evaporation and through ice-formation: see pages 12 - 13. (Tr.)

solid ice; consequently the bottom waters have little aeration. Here (though to a lesser degree than in frozen lakes) one finds stagnant areas, created by oxygen exhaustion and by the presence of hydrogen sulphide. In the second place, the bottom water temperature at some points in these regions always stays in the neighborhood of the freezing point. In the third place, we have seen that the ice-floes show only about a sixth or a seventh of their thickness above water. Such floes, driven by winds and by currents, often plow up the bottom of the sea at just these depths, destroying all life there.

In every sea moreover we know that life, particularly plant life, is found in particular abundance on tide-flats, and in the Arctic Seas these flats are frozen through and through for a great part of the year. The ice which forms there thaws out only from above and for that reason very slowly, so that the ice on the bottom often fails to melt during the short Arctic summer.

Hence it is not surprising that all these seas are very poor in fish and useful animal life. As exceptions one may mention the white grampus, which enters the Kara Sea in exploitable numbers as soon as the break-up takes place; also the walrus which congregates at resting grounds in certain sectors of the east coast of the Taimyr Peninsula, on Wrangel Island, and also on the sand-spits of the Chukhotsk Peninsula. In these seas only an occasional seal is encountered, and water-birds are not so numerous as in the Greenland and Barents Seas.

10. Ice Drift

Floe ice and pack ice are in a state of ceaseless movement, both winter and summer. The movements are of four kinds: first, the constant movements, caused by steady currents and by the steady prevailing winds which occur as a result of permanent regions of high or low atmospheric pressure in areas adjacent to the Arctic; second, the seasonal movements, which are connected with seasonal displacements of the centers of atmospheric activity; third, periodic movements caused by tide phenomena; and fourth, the ephemeral movements, which for the most part develop under the influence of ephemeral winds.

The courses of vessels drifting in the ice have shown that the ice-movements never follow a straight line. Ice fields may move now in one direction and now in another; sometimes they back-track over their course and sometimes they describe fantastic loops and zig-zags.

So far, the picture we have of the ice movements in the Central part of the Arctic Basin is still insufficiently precise. It is based on the study of a relatively small number of drift courses, and on the study of the courses of special buoys cast adrift in different regions of the Arctic Basin.

As far as can be judged from available observations, in all the minor seas of the Arctic the outward movement of ice into the Central Arctic Basin exceeds the inward movement of ice from that basin into the seas. In the heart of the Arctic Basin there seem to exist two fundamental systems of ice-movement. One of them is an outward movement of ice from the Arctic into the Greenland Sea, and is caused by the run-off of water from the land and by the prevailing winds; the other is in the nature of an anticyclonic swirl with its center located at 83-85°N 170-180°W and is the result of winds caused by the Central Arctic region of high pressure.

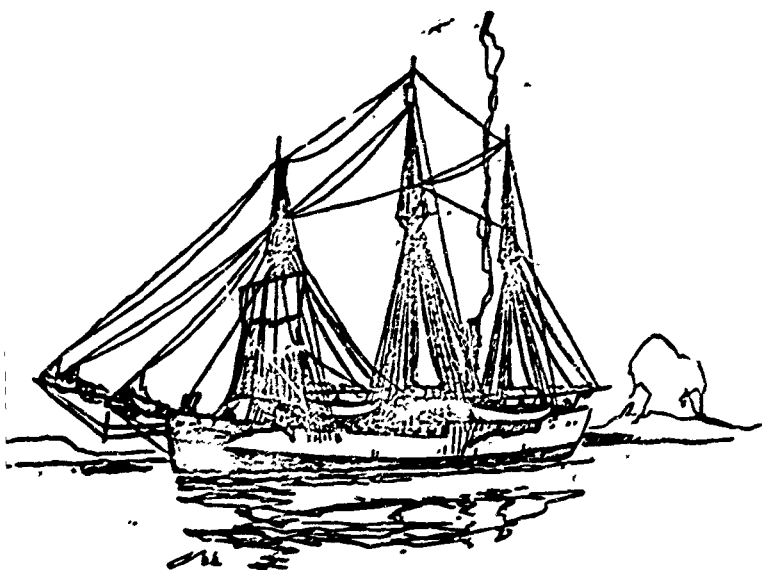
The existence of these two systems of movement is confirmed by all known drift-courses. Thus the Karluk under the command of Captain Bartlett in 1913-1914 drifted with the ice for a distance of 500 miles, approximately from Point Barrow in Alaska to Wrangel Island. In 1879-1881 the Jeanette commanded by deLong drifted from Wrangel Island to the New Siberian Islands, a distance of 750 miles. Nansen's Fram drifted from the New Siberian Islands to the straits between Spitzbergen and Greenland, a distance of 1400 miles. The Maud of the Amundsen Expedition in 1922-24 drifted from Wrangel Island to the New Siberian Islands, a distance of 750 miles. The drift of the Maud almost exactly reproduced that of the Jeanette, demonstrating that the direction of the ice movement is fairly constant.*

The ceaseless movement of the ice from east to west along the continental slope of the Eurasian Coast was also shown by observations made during the sled-expeditions of Parry, Cagni and Nansen; the movement along the continental slope on the North American side was shown by Stefansson's observations, made between 140 and 130°W and again between 130 and 110°W. Supporting evidence was furnished by numerous buoys set adrift by Soviet Expeditions in the Kara and Laptev Seas, and later picked up on the shores of Greenland, Iceland and Norway.

* See frontispiece Map II; see page 53. (Tr.)



The Jeannette of the DeLong Expedition.



The Fran.

Thus the ice-drift follows a single unbroken line along the periphery of the Central Arctic Basin from 160°W through 180° around to 0°, more than half way around the earth. This drift takes on the average 4.5 to 5 years, from the time the ice leaves Behring Strait until it is carried out into the Greenland Sea.

THE DIRECTION OF THE ICE DRIFT ON THE NORTH AMERICAN coast of the Arctic Basin has been much less studied. We have Peary's statement that during his numerous sled trips to the north of Greenland and Grant Land he found the ice to be moving from west to east, which means that here too it was heading for the broad straits between Greenland and Spitzbergen.

The observations of Station North Pole first showed that the ice from the North Pole was moving straight for the Greenland Sea.

During his expedition Nansen devoted a great deal of work to studying the details of the Fram's drift. He noticed that the Central Arctic ice fields responded very quickly to the wind, changing their speed and direction in accordance with changes of wind velocity and direction. Nansen's conclusions may be set forth in the following two simple rules:—

- 1) The speed of the ice drift is approximately 1/50th of the velocity of the wind causing the drift.
- 2) The direction of the ice drift deviates on the average 30° from the direction of the wind causing the drift.

The latter phenomenon Nansen ascribed to the influence of the side-thrust of the earth's rotation. This explanation is quite correct and furthermore rests on the same basis as the modern theory of oceanic currents, which I have already* discussed in detail.

Since then Nansen's rule has been verified by many Arctic expeditions and at many Arctic stations. Where departures from the rules were observed, they sometimes helped to explain very complex phenomena. Thus for instance the drift of the Fram ordinarily showed a deviation which fluctuated around 30° to the right of the wind direction. Yet when Nansen computed the mean wind direction for the whole three years and the mean drift of the Fram for the same period, then it turned out that the Fram had deviated 1° to the left. From this Nansen came to the conclusion that the Fram's drift was made up of two components, one caused by influence of local, ephemeral winds, the other connected with the general ice-circulation in the Arctic Ocean.

An example of fruitful study of the relation between wind and ice-field wind-drift is the discovery of Vizé Island in the northern part of the Kara Sea. This discovery was one which had long been foreshadowed by events.

As I have already mentioned, Lieutenant G.L.Brusilov's expedition in the St. Anna was caught in the ice on October 2nd 1912 off the West Coast of the Yamal Peninsula. The vessel was then carried out of the Kara Sea along the eastern coast of Franz Josef Land into the Central Arctic Basin.

* In an earlier chapter of this work, not here translated. (Tr.)

Only two members of the expedition reached Cape Flora on the 22nd of July, namely Al'banov, the mate of the vessel, and Konrad, a seaman. On the 2nd of August they were met at Cape Flora by members of Lieutenant Sedov's expedition in the St. Phoca, who were returning to Arkhangelsk.*

Al'banov's route to Franz Josef Land was of considerable interest in itself, because he crossed exactly those points where "Petermann's Land" and "King Oscar Land" are shown on the maps, thus proving that these lands do not exist. Even more important was the fact that Al'banov brought safely with him the log-book of the St. Anna and complete notes of meteorological observations for the whole period up to the time the ship was abandoned. This makes it possible to reconstruct the whole story of the St. Anna's drift.**

In 1924 Professor Vizé [Wiese] made an analysis of these observations and hit upon a curious fact in connection with the St. Anna's drift-course in the region 78 to 80°N and 72 to 78°E. Here the ship, drifting generally northward, showed a deviation to the left of the wind direction, not to the right as would follow from Nansen's rule. Vizé concluded that such a deviation could be explained if there was a land-mass not far to the east of the St. Anna's course, somewhere between 78° and 80°N. This predicted land-mass was indeed discovered by an expedition on the auxiliary ice-breaker Sedov in 1930, of which Vizé himself was a member. It turned out to be an island, lying between 79°29' and 79°32'N and at 76°46'E. Justly enough, it was given the name of Vizé Island.

From further analysis of the St. Anna's drift, it appeared that there should be still another island to the south of Vizé and to the north of Uyedineniye Island.*** No such island was discovered, but what was demonstrated was that Uyedineniye Island lay farther west than was shown on the maps.

Very interesting observations on ice drift were made by Station North Pole. Thanks to the numerous astronomical fixes of the position of the drifting ice field and exact instrumental measurements of its speed, we may produce a more detailed picture of its movements than was ever possible with any drift previously studied.

The plot of the drift shows that Station North Pole's ice field described fantastic zig-zags, sometimes even loops, but all the while maintained its general direction of drift from the pole to the Greenland Sea and beyond, along the eastern coast of Greenland.

The fact that the drift of the ice field depended on the wind was discovered during the very first month after the station was set up. Northwesterly winds prevailed in the vicinity of the station until approximately the 5th of June, and the ice field moved almost directly south. From the 5th to the 21st the northwesterly winds changed to southwesterly, and the ice field began to move east. In other words, the ice field changed its direction of movement under the influence of the wind.

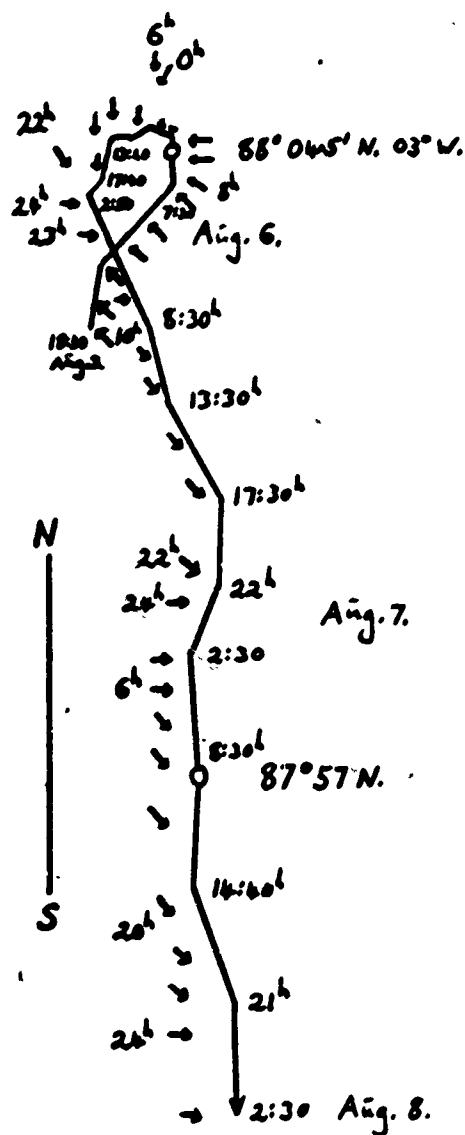
The speed of the general southward movement of the ice field also changed. The mean speed of drift for the whole period was about 9 km per day.

* See page 68.

** See frontispiece map II.

*** Called Einsackf Island on some charts. (Tr.)

Yet there were times when the ice field stayed in one place for some days at a time. At other times the daily movement speeded up to as much as 43 km. However, as the ice field moved southward the speed of drift steadily mounted. Thus from the pole to latitude 85° the mean speed of southward drift was about 5 km a day. From 85° to 81°N it increased to 9 km per day. In January it had increased to 21 km, and in February the mean daily speed of southward movement had grown to 23 km.



Relation between wind-direction and drift of Station North Pole from August 3rd to 8th, 1937.

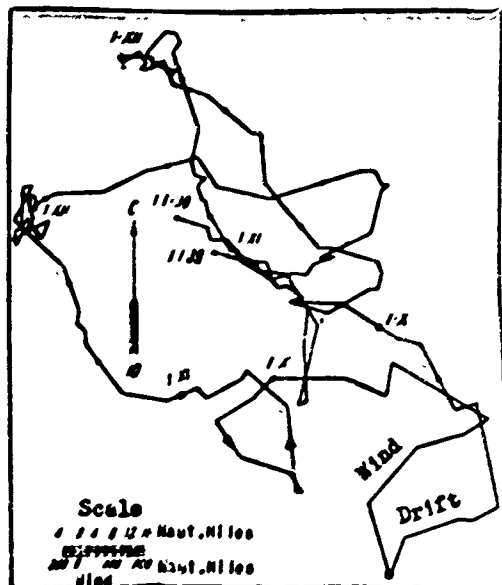
Preliminary studies of the drift of the ice field showed that it was due on the one hand to the influence of the wind blowing at any given moment at the place in question, and on the other hand to the influence of a general movement in a southerly direction and independent of the local wind. (When there was no wind the ice field continued to move southward.) Northerly winds accelerated this movement, while a south wind slowed it up or even cancelled out the constant component of the drift, causing the ice field to back-track northward, as may be seen from the diagram.

In the vicinity of the Pole, the speed of that component of the ice movement which was independent of the local wind amounted to approximately 2 km per day. Farther south however this component gradually increased until it reached 10 to 12 km per day in the region between the 70th and 75th parallels.

The drift velocity increased in a particularly noticeable manner when the ice field was approaching the shores of Greenland. It was not the wind alone which was responsible for the gradual increase in speed as the ice field moved farther south. Undoubtedly it was in some degree due to the greater freedom of movement of the ice field as it came into the open-water expanses of the Greenland Sea. Thus in August the mean wind velocity was somewhat higher than in December, and the wind direction was approximately constant. Nevertheless the ice field was drifting nearly three times as fast in December as in August. Here the leading role was played by the East Greenland Current, in which the ice-field was drifting in December.

All the zig-zags and loops of all drift-courses of which we have any record have been successfully related to the wind direction and speed.

This appears clearly in the diagram. It shows the drift of the Sedov and the "course of the wind" from the 1st of September 1938 to the 1st of January 1939, on the assumption that the Sedov and a certain given air particle described paths beginning at one and the same point on the 1st of September. The wind velocity is scaled down to the drift velocity, the former being reckoned as 50 times greater than the latter.



From the diagram it is seen that wherever the wind maintains its direction for a fairly long time, the drift of the Sedov is fairly constant.

In October the wind describes a "figure 8" and the Sedov describes very nearly the same "figure 8". At the end of November the wind is making zig-zags, and the Sedov is making similar zig-zags.

Thus the drift of the Sedov reproduces the "course of the wind", the only difference being that it is in a direction 30° to the right of the wind direction. If at some points the drift does show some departures from Nansen's rule, they must be regarded as due to incomplete information rather than as real.

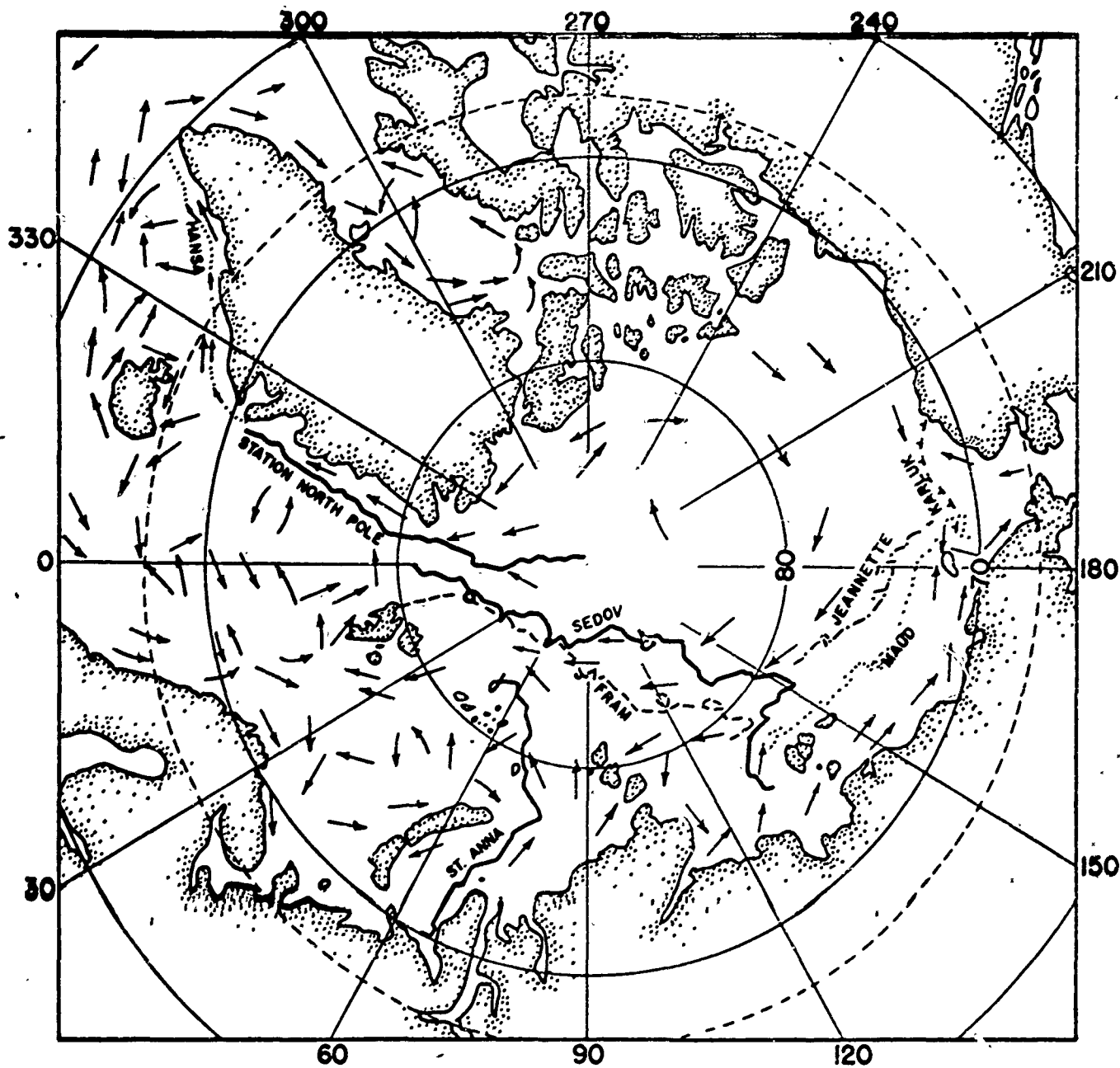
The "course of the wind" and the drift-course of the G. Sedov from Sept. 1st, 1938 to Jan. 1st, 1939.

Work done by myself on the Sedov observations has shown that in this region of the vessel's drift there was only a feeble prevailing current; for practical purposes it could be counted as non-existent. Thanks to this fact, I had what practically amounted

to laboratory conditions for my study of the relation between wind and drift. In this region, far from the distorting influence of land masses and of prevailing currents, the wind drift shows up in almost pure form.

It is clear from the diagram how reliable both of Nansen's rules are. One could not ask for fuller confirmation. I must once more emphasize that, in contrast to the data of previous polar explorers, the Sedov observations were made at a time when there existed in the Arctic a network of Soviet Arctic stations, and under conditions of a modern knowledge of the Arctic. These facts, together with the high level of precision in the Sedov observations, permit us to draw some very valuable conclusions. Thus, from further analysis of the Sedov drift and comparison with the atmospheric pressure maps compiled by the Weather Bureau for the period in question, I was able to supplement Nansen's rules by two more of the same simplicity:---

- 1) Ice drift is directed along the isobars. The sense of the drift is such that the region of higher atmospheric pressure lies on the right of the course, and the region of lower atmospheric pressure on the left.

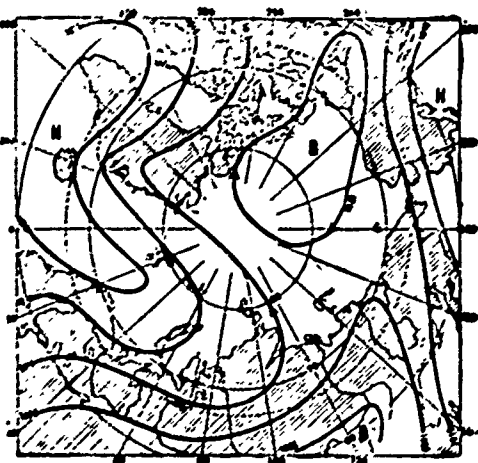


MAP OF ICE-DRIFT AND SURFACE CURRENTS OF THE ARCTIC OCEAN

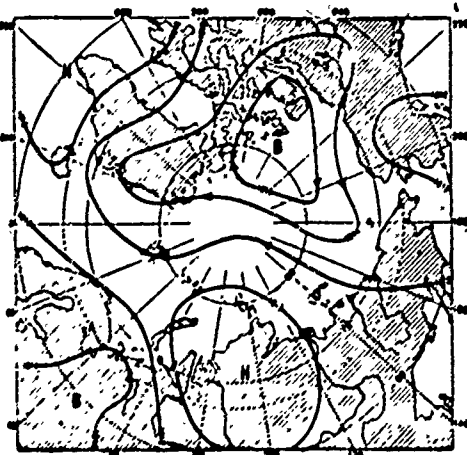
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- 2) Ice drift proceeds at a speed proportional to the atmospheric pressure-gradient; in other words, the drift speed is inversely proportional to the distance between isobars.

The first of these two rules is not at all difficult to deduce. In the high and middle latitudes, friction with the earth's surface and the effects of the Coriolis Force cause the wind to deviate approximately 30° to the left of the isobar. The ice-drift, according to Nansen's second rule, makes an angle of approximately 30° to the right of the wind direction. Thus it turns out that the ice must be drifting along the isobar.



Map of mean atmospheric pressure (in millibars) for the Arctic summer. The arrows show the basic ice movement.



Map of mean atmospheric pressure (in millibars) for the Arctic winter. The arrows show the basic ice movement.

And here is how my second rule was derived. When there are no prevailing currents nor distorting land-mass effects, the ice moves at a speed proportional to the wind velocity. The latter in its turn is proportional to the atmospheric pressure-gradient. The closer together the isobaric lines appear on the synoptic chart for any region, the stronger the wind in that region is. Hence the deduction, which is supported by other theoretical considerations, that it should be possible to judge from the synoptic chart not only the direction of the ice drift, but its speed also.

The charts here reproduced show the distribution of atmospheric pressure in the Arctic for summer and winter. From these charts one may see the broad features of the ice circulation in the Central Arctic, which in turn will explain all drifts and other phenomena.

However, from inspection of these charts it also transpires that in order to judge what direction the drift of an ice floe will take, or what course a ship drifting with the ice will take, it is not enough to know the position of the ship; that is, what point of the Arctic Basin is in question. One must also know the time of year.

If the Sedov at the beginning of April 1939 had been at the same latitude but farther over, approximately on the longitude of Behring Straits and not on the hundredth meridian as she actually was, then she would have been carried not into the straits between Spitzbergen and Greenland, but to the north coast of the American Continent.

Incidentally, the movement of the ice along the isobaric lines also explains the fact that the Maud, the ship of Amunsen's expedition, which entered the ice in 1922 off Wrangel Island for a

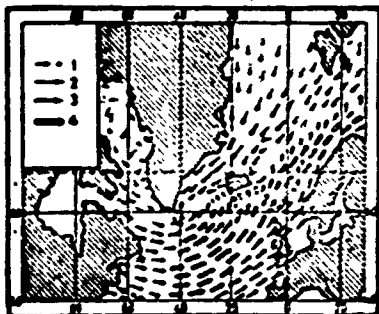
drift across the North Pole, was instead carried by the ice along the continental slope of the Asiatic Coast, that is along a parallel and not along a meridian. It appears that usually the isobars in the Wrangel Island region lie approximately along the parallels of latitude, particularly in the autumn.

It is furthermore apparent from the same atmospheric pressure charts that both in winter and summer one sheaf of the isobaric lines ends up squarely on the northern coast of Greenland. The effect is to create there a region where massive ice formations accumulate, to which certain people have given the name of palaeocrytic ice. Another sheaf of lines runs out of the Arctic Basin into the Greenland Sea, thus causing the flow of ice in that direction ... the Ice Stream.

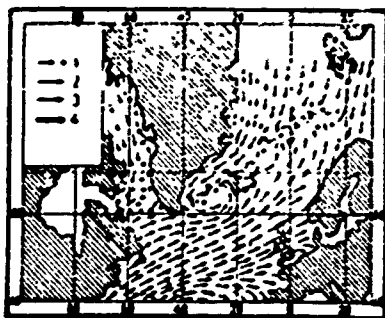
11. The Ice Stream

Starting out on its drift from the North Pole southward to latitude 81° , the ice field of Station North Pole entered the Greenland Sea and began to move over the broad belt of shallow water on the east coast of Greenland.* Here

In January and February.



In July and August



Distribution of wind directions and strengths over the northern part of the Atlantic Ocean and the North European (Greenland) Sea. The thickness of the arrows shows the different ranges of wind-velocity

it was caught up in the great Greenland Ice Stream, an unbroken ribbon of ice floes moving along the eastern shores of Greenland, from North-East Cape to Cape Farewell at the southern tip, and then ascending northward along the coast into Baffin Strait. This stream of ice flows continuously both summer and winter, and is one of the most remarkable of Nature's phenomena, although it is less familiar to people than the Gulf Stream.

How does this Greenland Stream, or East Greenland Current, originate? Each year there pour into the Arctic Ocean about 3,000 cu. km. of river water, about 20,000 cu. km. of Pacific Ocean waters through Behring Strait, and over 50,000 cu. km. of warm Atlantic waters from the Norwegian and Greenland Seas. All this enormous volume of water must of course get out of the Arctic Basin somewhere; either get out or pile up. A small portion of it flows into Baffin Strait through the numerous but shallow channels of the American Archipelago. However, the bulk of it (about 80,000 cu. km.) makes its way into the Greenland Sea through the straits between Greenland and Spitzbergen, thus creating the East Greenland Current.

The charts on this page showing the prevailing wind directions for January to August, plus the diagram of the

prevailing currents in the Greenland and Norwegian Seas and the isobaric charts for the summer and winter seasons, will demonstrate the fact that this current, even though it is in the nature of a discharge or escape of water, is nevertheless at the same time controlled by the prevailing winds; that is, it is a drift-current.

The East Greenland Current is so strong that it not only carries off the whole of the water which pours into the Arctic Basin, but also it sucks in and drags back some of the Atlantic waters which are flowing in to make up for part of the efflux.

* See frontispiece maps

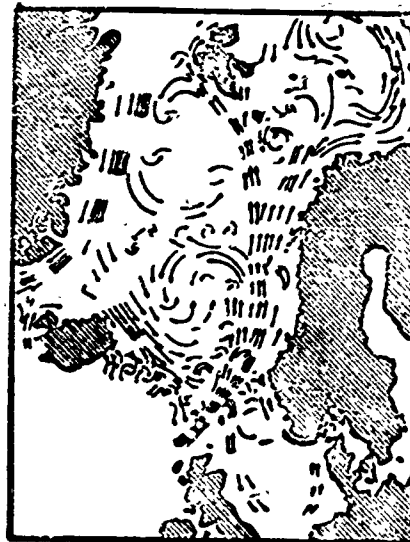


Diagram of currents at the surface of the Greenland and Norwegian Seas (acc. to Nansen).

The Eastern boundary of the Greenland current stays in practically the same position all the year round. It runs approximately along the eastern limits of the continental shelf which engirdles Greenland. Thus the ice stream is as it were confined to the waters of shallow depth.

The ice in the Greenland Stream may be divided into three parallel streams. The westernmost, that nearest to the shore, consists of ice formed in the many fjords of Greenland, and carried out along with the icebergs which fill these fjords. The middle stream consists of the pack ice which drives into the Greenland Sea from the Central Arctic Basin. It was in this stream that the ice field of Station North Pole drifted. Finally, the eastern (outermost) stream is made up of ice driving into the Greenland Sea from the regions of Spitzbergen, Franz Josef Land and Severnaya Zemlia, including the ice which forms in the Greenland Sea itself.

The speed of the Greenland ice stream is not uniform throughout its length: at 81°N its speed is about 3 to 3.5 km per 24-hour day, gradually increasing to the southward and reaching 20 to 25 km per day in the Denmark Strait (between Greenland and Iceland). The three parallel streams moreover do not have the same speeds. Apparently the middle stream is the fastest.

The non-uniformity in the speed of the stream was a fact previously known, but it was demonstrated with particular clarity by the drift of Station North Pole.* During the time when the ice field was drifting in the Arctic Basin, its orientation relative to the northern land-masses did not change. This gave the impression that in spite of all the meanderings of its course it was participating in a general movement of a vast expanse of ice fields.

But when the ice field had come into the Greenland Sea, it began to rotate, first in one direction and then in the other, a motion which was certainly due to a current set up by the unequal velocities of different fields.

The increase in the speed of the Greenland ice stream toward its more southerly parts is accompanied by a decrease in its width. Thus on the 80th parallel the width of the stream reaches 400 km, while on the 70th parallel it has decreased to 200 km.

More than one attempt has been made to estimate the amount of ice carried through the straits between Greenland and Spitzbergen. So far however we have no proper figures, because we lack information on the mean thickness of the floes, on the changes of velocity taking place in different seasons of the year, on the area of the sea surface occupied by the ice, and so forth.

According to Vizé's calculations the efflux of ice amounts to 8,000 cu.km. annually; but according to my very cautious reckoning it is less than this. If the Greenland Current, thanks to the characteristic winds associated with it, is of a very steady nature, and if its speed is about 8 to 12 km per day at the points where its width is 200 km, the result I obtain is that this current carries up to 1,000,000 sq.km. of sea ice out of the Arctic Basin each year; that is, the ice from 13 to 20% of the whole area of the Central Arctic Basin. On the conservative estimate that the ice drifting with

* See Frontispiece Map 1.

the Greenland Stream has a mean thickness of 3 m, we have for the annual efflux of ice the figure 3,000 cu. km., or about 2,500,000 million tons. In melting this ice, over 170×10^{18} gram-calories of heat are absorbed.

The ice coming from the Arctic thaws in the more southerly latitudes and takes up an enormous quantity of heat, thus increasing the severity of the climate in the adjacent regions. One may say that the glacial stream exports cold from the Arctic, while the waters of the rivers and of the Atlantic are importing heat. We must always bear in mind that in the formation of ice an enormous amount of heat is liberated and given off to the atmosphere. The figures for the amounts of heat imported into the Arctic and of cold exported from the Arctic do not remain the same from year to year. They vary, and the variations are reflected in a very real manner in the weather conditions of Northern Europe and in the ice conditions in the western seas bordering the Arctic.

Thus the observations of Station North Pole are particularly valuable because, supplementing as they do the previous observations made by Soviet explorers in the Greenland Sea, they enable us for the first time to make a quantitative estimate of the amount of ice carried out of the Arctic Basin and to follow up its life history. At the same time the results of Station North Pole's work bring up new and extremely important problems.

First of all the following question arises: was the fairly high drift speed of the Station usual for the Greenland stream, or was it only a function of the particular weather conditions of the winter of 1937-38? And how much connection has it with the general re-warming of the Arctic?

In the history of Arctic exploration many cases are known of vessels drifting with the Greenland ice. For instance at the time when operations were in progress for abandoning Station North Pole, there was the Soviet vessel Murmanetz, which was caught in the ice to the south of Jan Mayen and was then carried through the Denmark Strait into the regions south of Iceland, where she finally got clear.

The most notable cases of ships drifting with the Greenland ice are the following. In June 1777 some vessels of the Dutch whaling fleet were caught in the ice at 76°N and were carried southward through the Denmark Strait at a speed of 18 to 20 km per day. The Hansa, a sailing vessel belonging to a German Arctic expedition, entered the ice on the 14th of September 1869 at $73^{\circ}25'\text{N}$, $18^{\circ}40'\text{W}$, seventy kilometers off the eastern coast of Greenland, and was carried southward. On the 22nd of October 1869 the Hansa was crushed by the ice at $70^{\circ}52'\text{N}$, 21°W (that is, a little to the north and a little to the west of the point where Station North Pole was abandoned). The men of the Hansa drifted on an ice floe along the eastern coast of Greenland and after a 200-day voyage to position $61^{\circ}21'\text{N}$ 42°W took to their whale-boats and made the Greenland shore. During their whole drift they covered a distance of nearly 2,000 km. Because the point where Station North Pole was abandoned is the same as the point where crew of the Hansa began their drift on the ice floe, we are able to calculate the ice drift over the whole enormous distance from the pole to the southwest coast of Greenland.*

* See chart facing page 53. (Tr.)

It was already known that the ice fields of the Central Arctic, when they arrived in the Greenland Sea, were of comparatively large size, while numerous observations made by vessels engaged in scientific and commercial pursuits had made it clear that in the regions between Jan Mayen and Iceland only fragments of these fields were encountered, measuring approximately 30 to 50 m in diameter. To these fragments of thick ice fields the Danes and Norwegians give the name of stor-is, meaning large ice. Thus it was clear that in the region between North-East Cape and Jan Mayen a break-up of the great Arctic ice floes must be in process, but the exact nature of this process was unknown.

As long ago as the Cheliuskin drift it was noticed that at times, particularly during periods of hummocking of the ice fields, the ice was traversed by something like waves, under the action of which the fields would begin to rock. This phenomenon was known to Shirshov and Krenkel' of the Cheliuskin; hence during the Station North Pole drift careful observations were made of the behavior of the levelling bubble in a theodolite set up on the ice field for the purpose of indicating these oscillations.

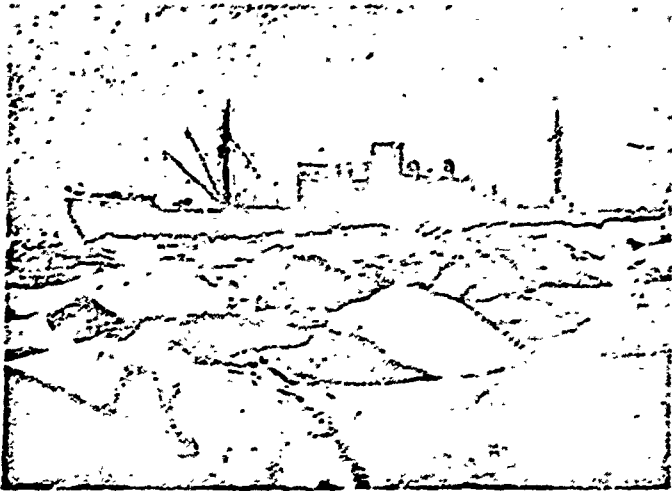
The ice field of Station North Pole at first drifted in an extremely quiet fashion. The crew of the station sometimes discovered crevices in the field, formed by the effect of temperature variations, but up to the end of January no hummocking nor severe shocks were observed. Moreover, particularly at the start of the drift, there were only comparatively small turning movements around the vertical axis.

The first heavy shock was noticed on the 20th of January. The first oscillation in the theodolite level was not detected until the 21st of February 1938, when the ice field was in the Greenland Sea at approximately 77°N.* Doubtless this had something to do with the fact that the whole of that January in the Greenland Sea was stormy; the wind velocity not infrequently reached 30 m/sec. Because of this strong wind and the fact that the eastern part of the Greenland Sea is always free of ice, the field had picked up a certain amount of motion.

On the 26th of January a storm broke which continued for six days, and the ice field started to rock more strongly. This motion had a period of 10 to 12 seconds, that is, approximately the period which is observed in case of ocean storm waves; the inclination of the ice field reached 60 seconds of arc, or even more. As a result of this rocking, stresses were set up in the ice and finally, on the 1st of February, the field broke up along lines approximately at right angles to the wind direction. Beyond doubt, the cause of this oscillation and break-up was the heavy swell created by the storm winds in the nearby ice-free stretches of the Greenland Sea and travelling outward (in accordance with physical laws) in all directions.

After this disintegration of the ice field, the crew of Station North Pole found itself on an ice floe of dimensions 30 x 50 meters, separated from other floes by rifts 1 to 5 meters wide. When the wind died down, the floes began to approach each other and freeze together. On the 19th of February, the day when Station North Pole terminated its operations, the distance

* In the case of the Sedov, the first oscillation of the theodolite level was observed on the 2nd of January 1940 at 81°01'N 30°18'E. The margin of the floes was then at latitude 80°N.



The Chelivukin in the heavy ice of the Chuckchee Sea.



Taking depth soundings at Station North Pole.
I.D. Papanin and A.S. T. Krenkel' at the wind-
lass. E.K. Fedorov awaiting his turn.

of the Station from the edge of the field on which it found itself had already grown to about 2 km. But the new field which was freezing together out of the fragments of the old was of course not so strong; from that time on, winds even of small force could have broken it up very quickly.

12. More about the Isobaric Drift of the Ice

I have already mentioned that my results in analyzing ice drifts enabled me to establish two rules, which were later confirmed by mathematical calculations, namely.

- 1) the ice drifts along isobars, keeping the region of high atmospheric pressure on the right;
- 2) the ice drifts with a velocity proportional to the gradient of the atmospheric pressure.

Nevertheless some research workers are still continuing to look for a relation between the speed and direction of the wind and the speed and direction of the ice drift. If in doing so they come upon cases of the ice drifting when there is no wind, they usually ascribe them to the effects of prevailing or other ocean currents. Here however they are losing from sight the fact that the wind is the consequence of the distribution of atmospheric pressures, and the wind-drift is in turn a consequence of the wind. Is it therefore not simpler to look for a relation between the ice drift and the distribution of atmospheric pressure?

Here are some proofs of the usefulness of this method.

Let us, like N.K. Khanaichenko, suppose that in a certain region there are (as is usually the case) areas of high and low atmospheric pressure (cyclones and anti-cyclones), arranged in a checker-board fashion. Such an arrangement is shown in the diagram. The arrows indicate the direction of the ice drift

along the isobars. Points O' and O'' are called neutral or hyperbolic points. They are characterized by a complete absence of wind. Lines AB, CD and EF are called asymptotes. The theoretical calculated speed of ice drift along these lines is indicated by the length of the arrows along the asymptotes.

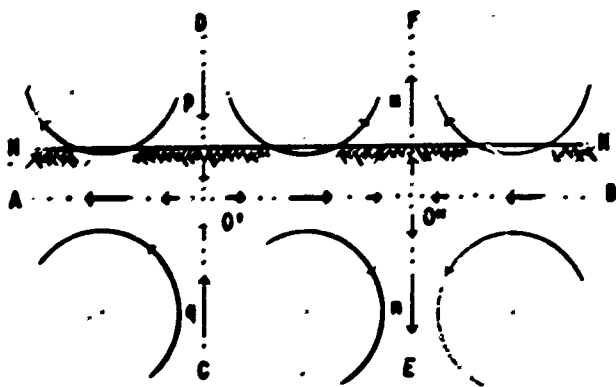


Diagram of ice-movements at neutral points of a barygraphic system.

If as we go along an asymptote the drift speed is increasing, then naturally under these circumstances a packing of the ice floes is taking place; if it is decreasing there is a dispersal or thinning out of the floes. Thus for instance in the direction from point O'' toward points m and n the floes are being thinned out. In the direction from points p and q toward point O' the floes are being compressed.

MN in the diagram represents a shore-line; above it lies the sea. From the sketch it will appear that in spite of there being little wind in the neighborhood of point O" the ice is here being carried away from the shore and dispersed, while at point O' it is being driven against the shore and compressed.

The spatial arrangement of the barygraphic systems in the figure and the position of the shore-line are very like situations to be found on the northern coast of Siberia. In the neighborhood of point O' we find approximately reproduced just such conditions as are observable to the north of Aion Island from November to March. Since in the remaining months of the year there is either little wind or a prevalence of northwest winds in this region, this is where an ice pack builds up (the Aion Pack), hanging as it were over the coast from the north and constituting a continual threat to shipping between the East Siberian and Chuckchee Seas.

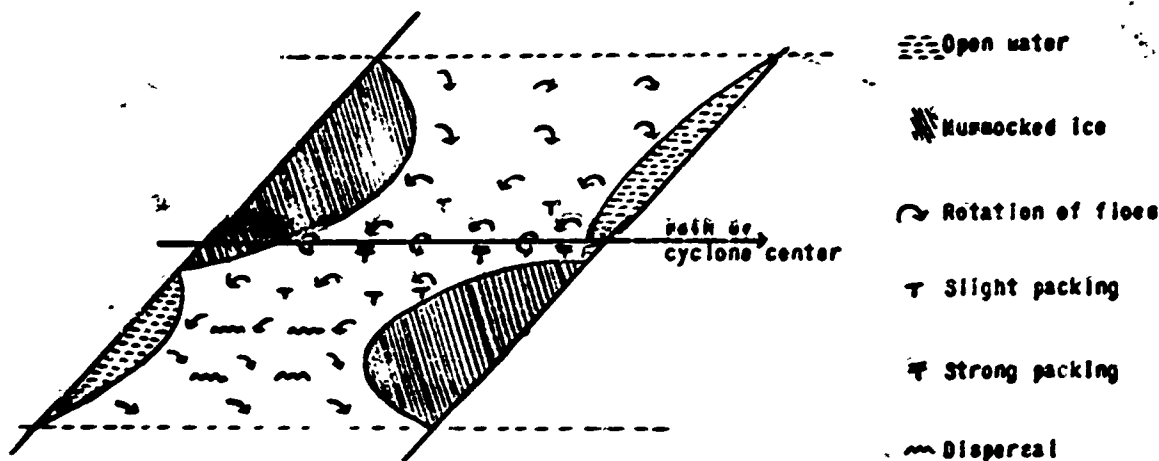
From the 21st to the 26th of August 1946, I was flying over the ice in the Kara Sea and Vil'kitzki Strait, over the ice of DeLong Archipelago, over the Aion Pack and the ice of the Chuckchee Sea. Nowhere else have I ever seen such massive and hummocky ice as in the Aion Pack. In all other seas of the Soviet Arctic, single-year ice formations predominate. Even if these formations survive the Arctic summer, they are carried out into the Central Arctic in the course of the next winter. But the ice formations of the Aion Pack are perennial in character and only a small amount is carried off by winds and currents during the summer season through DeLong Strait into the Chuckchee Sea.

If we accept the thesis that the ice drifts along the isobaric lines and with a speed proportional to the pressure gradient, then the floes will move without changing their relative position only when the isobars form perfect circles and when in the barygraphic system the relation between the pressure gradient and the distance from the center of the system is the same at all points. Under all other conditions the floes will be drifting with different angular velocities; the relative positions will be ceaselessly changing. In one and the same barygraphic system, even when the system as a whole has no motion, areas of packing and of dispersal will be created.

Very interesting results may likewise be obtained when we use the ice-drift rules to study the effects of a moving barygraphic system on the distribution of floes.

Let us suppose that a cyclone with circular isobaric lines and a constant pressure-gradient is cutting at an angle of 45° across a parallel-walled channel full of evenly distributed ice floes.

In the diagram (over page) are shown the path of the cyclone center and the edges of the strip it affects, the regions of packing and dispersal, and also the direction of rotation of the ice floes. It will be clear that by assigning various positions to the banks of the channel and varying the direction of the cyclonic path in relation to them, we may cause this setup to reproduce approximately just such conditions as are actually found to exist. If we make certain recognized assumptions we may for instance even



Distribution of hummocking, polynias, and rotation of floes during passage of cyclonic depression over a straight channel.

apply this scheme to the Kara Sea. Thus if the path of the cyclone runs from west to east somewhere in the region of Cape Zhelaniye, the result will be the formation of the Novaya Zemlia polynia; if the path of the cyclone lies approximately along the latitude of Yugorski Shar, then a polynia will be formed extending along the Yamal Peninsula.

In making such calculations one should bear in mind that, with the same wind strength but with different amounts of ice, the movement of the boundary of the floes toward the shore or toward the icefoot, whether by packing or by hummocking, will not always take place at the same speed. It takes considerably less time to pack the floes when the ice-coverage is 5/10 or 6/10 than when it is 8/10 or 9/10.

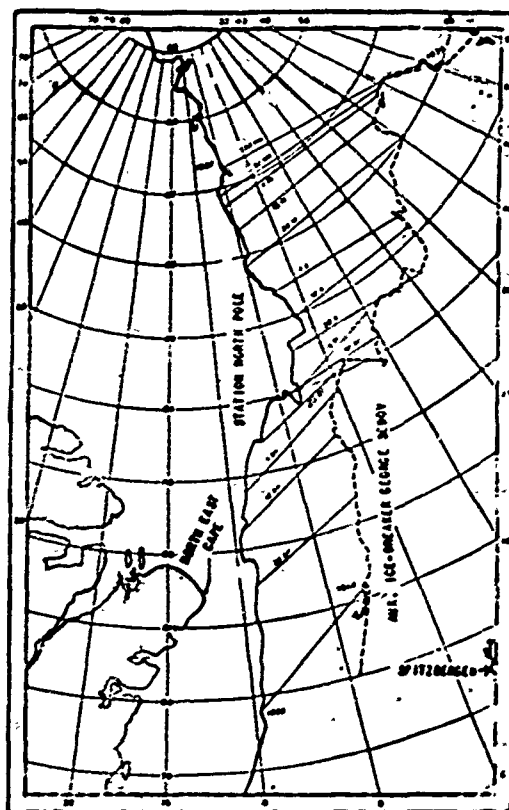
The same of course applies to hummocking.

In conclusion I should mention that the steepest pressure gradients are observed in small, rapidly moving cyclones. Yet even though the wind in this case may reach a high velocity, it is changing its direction so rapidly that the effect of such cyclones appears only in the breaking-up and hummocking of the ice fields, without any considerable drift being caused. A similar phenomenon may be observed where the sea is clear of ice; indeed I have already mentioned the fact that rapidly-moving barygraphic systems are incapable of creating any noticeable currents in the sea. They make their influence felt mainly in agitating the surface layers of the ocean.

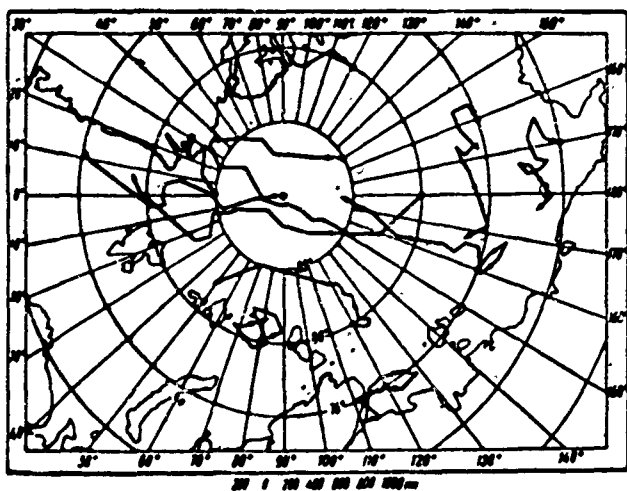
At the Weather Bureau they compile a daily synoptic chart of the distribution of atmospheric pressure, showing the isobaric lines. From these charts it is easy to read off the direction of the isobars and the distances between them for any given point of the earth's surface. With these data it



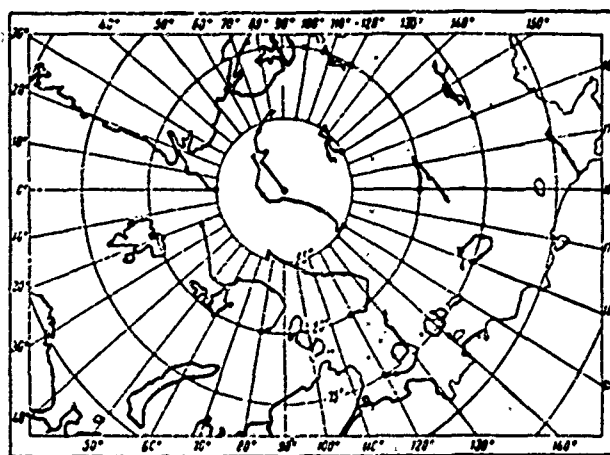
Distribution of atmospheric pressure over the Arctic Basin in Jan. 1939, with ice-drift. The thin arrows show the direction of ice-movement, the heavy arrow, the drift of the Sedov.



Drift of Station North Pole and of the Sedov before being carried into Greenland Sea.



Calculated drift of Arctic ice, 1937.



Calculated drift of Arctic ice, 1938.

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is not difficult to calculate the speed and direction of the ice movement in any region of the Arctic Ocean.

I here reproduce a chart of the mid-month atmospheric pressure over the Arctic Ocean for January 1939, and on it the direction of the Sedov's drift during that month. As we see, this drift coincides exactly with an isobar.

On the same chart there is shown the ice-drift in different parts of the Arctic Basin for January 1939. It will be seen that the floes of the Central Arctic basin are not moving as a single mass, but in different directions at different speeds. There are zones of swift movement and relatively stationary zones. Where the arrows converge, packing and hummocking is taking place; where the arrows diverge, the ice is dispersing and spaces are opening between the ice fields.

However, the distribution of atmospheric pressure over the Arctic Basin is changing not only from month to month or from season to season, but from year to year also. And therewith the circulation of the ice, determined by the barygraphic contours, is likewise changing from year to year and indeed over a quite considerable range.

The other two charts show the Arctic ice-drift in 1937 and 1938. The small circles on these charts show the positions, on January 1st of the year in question, of certain ice floes the courses of which are traced until the end of the year. These ice-drifts were calculated by M.M. Somov from the monthly synoptic charts of atmospheric pressure.

It is understood of course that these charts are intended only as a rough illustration. In compiling them, no allowance was made for the effects of currents and shore-lines. Yet they do give an idea why it should be that in 1937 the efflux of ice into the Greenland Sea was considerably greater than in 1938.

However, the most important thing shown by these charts is that it is out of the question to discuss ice drift in terms of any simple-looking scheme of short-distance movements. On the contrary, we have to recognize that there exists in the Central Arctic Basin a complex circulatory system which is subject to considerable variations over any interval either of time or of distance. It is the inequalities of drift (particularly the variability with time) that account for the appearance of areas of hummocking and dispersal, areas of stagnation and of accelerated movement.

The dependence of the ice-drift on the isobaric picture is a concept which adds much to our understanding of the nature of the currents in the Arctic Basin.

The general pattern of atmospheric circulation over the Arctic Basin is such that it is the main factor which keeps the ice moving in the direction of the Greenland Sea. The wind-driven circulation of the ice brings into movement the surface layers of water supporting the floes. It is wind-action over the whole area of the Arctic Basin, independently of local winds, that creates the surface current which in the Greenland Sea is strengthened by the

northerly winds prevailing there.

I should add that the character of the atmospheric circulation may change from season to season and from year to year in such a manner that only certain localities experience accelerations of the ice-drift. For instance, if the ice efflux from the region adjacent to Behring Strait is strengthened, the influx of Pacific Ocean waters from the Behring Sea may be proportionately strengthened, while the efflux of ice into the Greenland Sea and the influx of Atlantic waters remain unaffected.

If the ice movement is such that it is retreating from some section of the coast, then of course we may expect good conditions for navigation there during the summer.

Any movement of the Arctic pack ice away from the coast is followed by an intensified efflux of the local ice which forms in the marginal seas. On the other hand, when the pack-ice moves shoreward the efflux of the local ice is arrested. Often indeed it happens that the marginal seas are choked with ice from the Central Arctic Basin, in which case navigation conditions on the Northern Sea Route deteriorate proportionately.

From this it is clear how important the new rules are for our ice forecasts, particularly the long term forecasts. In fact if we use my method to keep track of the movements of the different Arctic ice packs throughout the winter and spring, we may estimate the general ice conditions for the following Arctic navigation season.

The new rules are no less important in making the short-term ice forecasts which inform us of the distribution of ice in individual sectors of the Northern Sea Route. These forecasts are based on the observations of meteorological stations and on ice reconnaissance carried out by aircraft and patrol vessels during the Arctic navigation season. However, the station-observations cover only a coastwise strip of the sea, while ship and aircraft observations cannot be maintained uninterruptedly nor can they take in all areas. Here is where we must have recourse to continuous plotting and tracking of ice-field movements on the daily weather map, using the method which we have discovered.

That this has been made possible is one of the greatest practical achievements of recent times. It was made possible by the splendid work of an outstanding team of Soviet Arctic-men, a team brought into existence by our great Stalin.

CHAPTER VII

THE WARMING OF THE ARCTIC

Seamen have long found it astonishing that the amount of ice encountered during the summer navigation season in the marginal seas of the Arctic should vary so much from year to year. After periods of very little ice, when navigation in the high latitudes is possible for any type of ship, there will be years when even the most powerful ice-breaker cannot penetrate those very same regions.

Besides fluctuations in the amount of ice in each individual sea, we have in recent years witnessed a general warming of the Arctic, which began approximately in 1920 and manifested itself in higher air and sea temperatures, and in a decreased amount of ice. The following facts are indicative of this general warming of the Arctic.

1) The retreat of the glaciers and the thawing out of islands.

Since approximately the beginning of the present century all the Greenland glaciers descending into Northeast Bay* and Disko (on the west coast of Greenland) have been retreating. The Jakobshavn Glacier in particular has retreated almost 20 km in the period 1880-1920. Incidentally, the glaciers in these two bays produce the bulk of the Greenland icebergs.

The retreat of the glaciers has likewise been observed of late on Spitzbergen, on Franz Josef Land and on Novaya Zemlia. It is a striking fact that in recent years some islands of Franz Josef Land have seemed to split in two. Previously they had been joined together by necks of ice.

During my cruises on the Perseus in 1934** and on the Sadko in 1935 I diligently compared what I saw with the descriptions and photographs of the glaciers on Jan Mayen Island and Spitzbergen, as given in the British Arctic Pilot for 1911. Everywhere I noticed great shrinkages in the dimensions of the glaciers. In the case of the Spitzbergen glaciers, the retreat and disintegration observed in recent years has been described by some writers as "catastrophic".

Phenomena of the same type are the already-mentioned northward retreat of the southern permafrost boundary, and the thawing out of frozen soil and fossil ice deposits.

2) Higher atmospheric temperatures.

Since 1920 there has been a rise of the mean temperature of the winter months on the shores of Baffin Strait and on the coasts of the Greenland, Barents and Kara Seas. Even in the winter of 1928-29, when there were intense cold-spells in Europe, the winter temperature on Spitzbergen and Bear Island was only a bit below normal.

In the whole Arctic sector from Greenland to Cape Cheliuskin there has not been since 1930 a single negative anomaly in the mean annual and

* An old name. Disco Bay was formerly called Southeast Bay; Northeast Bay is probably Umanak Fjord. The Geographical Branch of the Dept. of Mines (Canada) refers me to an old Hudson's Bay Co. map published by Arrowsmith, London, 1832. It shows a N.E. or Jacob's Bay (compare Jakobshavn) at a location suggesting Umanak. (Tr.)

** See page 29. (Tr.)

monthly temperatures, and the positive anomalies were quite high. Thus in the winter of 1934-35 the positive anomaly of the mean monthly temperatures in the region from Dixon Island to Cape Cheliuskin was as much as 4 to 10°C. In November 1935 the positive anomaly of the Spitzbergen atmospheric temperature reached 10°C.

If we compare the mean atmospheric temperatures registered on board the Fram and on board the Sedov, at times when the two ships were under roughly the same conditions as regards geographic position and season of year,* it is apparent that the mean annual temperature registered on board the Sedov was 4.1° higher than that registered by the Fram. During the winter season (from September to February) this discrepancy increased to 7.5°.

3) Higher temperature of the Atlantic Ocean waters flowing into the Arctic Basin. As we have seen, an offshoot of the Atlantic, the so-called North Cape Current, flows into the Barents Sea. Since 1898, temperatures in this current, from the surface to the bottom of the sea, have been quite regularly observed. A particularly intensive observation of the North Cape Current was commenced during the Soviet era. It has been learned that its mean temperature for the period 1921-1936 was 0.7°C higher than the mean for the period 1900 to 1906. What this signifies is that a column of North Cape Current water, with a cross section of one square centimeter and a depth of 200 meters, has 14,000 more gram-calories of heat stored up in it today than it had at the beginning of the present century.

The warming effect of the Atlantic waters flowing into the Arctic is also manifested in the region adjacent to Franz Josef Land and Spitzbergen.

It is well known that everywhere in the Arctic the warm Atlantic water is overlaid by a layer of very cold Arctic water of comparatively low salinity. During the last century the lower boundary of this layer of Arctic water off Spitzbergen and Franz Josef Land was observed to lie at a depth of 150-200 meters. At the present time this boundary, in the same regions, is found at a depth of 75 to 100 meters.

The heating effect of the Atlantic water appears even more markedly in data obtained from depth soundings in the Arctic Basin. For instance not one of the Fram's soundings in the Arctic Basin gave a temperature exceeding 1.13°C for the deeper-lying waters of Atlantic origin. The Sadko expedition in 1935 observed temperatures up to 2.68°C for these waters, while the Sedov got temperatures of up to 1.8°C in the areas to the north and east of the Fram's drift course, where the water should have been colder. If we compare the Sedov soundings with the closest neighboring Fram soundings, then we find that for each square centimeter of the surface of the central part of the Basin the stored heat is today nearly 80,000 gram calories more than it was in Nansen's time.

4) Decrease in the amount of ice. According to calculations made by Karelin, the area of the ice in the Greenland Sea in the April-August period of the years 1921-1939 was 15 to 20% less than for the years 1898 to 1920. According to my own figures, the amount of ice in the Barents Sea, for the same months and for the years from 1920-1933, was 15% less than for the years 1900-1919.

* See frontispiece Map II. (Tr.)

The southern part of the Kara Sea (south of the latitude of Matochkin Shar) has been ice-free in September of every year since 1929. Over the period 1869-1928 the probability of meeting ice in September, in this region, was about 30%.

During the last century and at the beginning of the present century the Arctic ice floes would sometimes reach to the shores of Iceland and interfere with fishing and navigation there. During the past thirty years the ice showed up off Iceland in 1929 only, and then in insignificant amounts.

Until the year 1920 the Yugorski Shar used to freeze over, on the average, two months earlier than it did, on the average, between 1920 and 1937.

When the sea is covered with ice, the amplitude of the tides is as a rule diminished. Vizé notes that in the case of Franz Josef Land and Dixon Island it has increased 15 to 20% during this period of Arctic rewarming.

5) Sea-borne traffic. The fact that ships have reached high latitudes is not always a good index of the amount of ice present in the region. Choosing the proper course and choosing the proper moment might mean success for one vessel, while another ship of the very same type might not choose so correctly, and thus create the impression that the region in question was quite impassable on account of ice.

It is very difficult to compare voyages (particularly along the Northern Sea Route) made under present-day conditions with those made at the beginning of the century, because today we have this route under much better control. Our far-flung network of radio and meteorological stations, our ice-reconnaissance (sea and air), our navigation charts, beacons and markers and, last but not least, our accumulated knowledge and experience all make present-day navigation considerably easier than in times gone by. Nevertheless it is fair to cite a number of voyages which were unheard-of during the previous colder periods. Among these are the voyage of our motor sailing-vessel Knipovich around Franz Josef Land in 1932 and the through-trips made by ordinary steamships over the whole length of the Northern Sea Route in 1935, no ice being encountered anywhere on the course. And so on.

It is a well-known fact that since 1930 there has not been a single year when it was not possible to round Novaya Zemlia on the north with vessels unequipped for ice navigation. Yet it is also a well-known fact that in 1901 Makarov's attempt* to round the northern tip of Novaya Zemlia from the west, on the ice breaker Yermak, ended in failure, although the Yermak spent nearly a month fighting the ice off the northwest shores of the Island. And we remember 1912, when the St. Phoca of the Sedov Expedition* was unable to get through to Franz Josef Land and had to winter off the northwest coast of Novaya Zemlia. The same year, the St. Anna of the Brusilov Expedition* was caught in the ice off the Yamal Coast.

* The following details are from Chapters 2 and 3 of Zubov's work, chapters not included in this translation.

1) Admiral Stepan Osipovich Makarov was the first to suggest taking a vessel to the Pole by active means, rather than by passive drifting. He proposed to use a powerful icebreaker, and designed the Yermak for the purpose. With this ship (built for him at Newcastle-on-Tyne) Makarov tackled the ice north of Spitzbergen in 1899-1901. In two attempts he got only as far as 81°21'N, the ice proving too much even for the mighty Yermak.

In spite of failure, Makarov's work bore fruit. His book, "The Yermak in the Ice" is still the

During the last 15 or 20 years, navigation conditions have become incomparably better than they were before, at least in those waters which have been most studied from the point of view of ice, namely the Greenland, Barents and Kara Seas.

6) Biological signs of the warming of the Arctic. During recent years the species of fish useful to mankind have been spreading farther and farther north. Since 1921 cod have been appearing in great numbers off the shores of Spitzbergen and Novaya Zemlia, and fishing in the northern waters has consequently increased. In the Barents Sea, European fishing vessels have increased their catch from 30,000 tons in 1924 to 97,000 tons in 1930. Off the coast of Greenland the catch has risen from 300 tons in 1926 to 48,000 tons in 1930.

The waters which wash the shores of Norway, Bear Island and Spitzbergen now furnish the countries of Northwestern Europe with 20% of their total Atlantic catch. In 1924 the total output amounted to 544,000 tons; by 1930 it was 753,000 tons. The increase is mainly due to our better mastery over the northern fishing areas.

Thus the center of gravity of the world fishing industry has in late years been shifting gradually to the Arctic waters, and the fact must be ascribed to the warming of these waters.

Of course a shift of this kind is perhaps not a satisfactory indication, because fish normally make long excursions (migrations) from one region to another. But the bottom-water organisms of little motility have also been shifting northward of late, a fact which likewise points to a warming of the Arctic. Many warm-water forms (echinoderms in particular) which the Murmansk

bible of the Russian Arctic navigator.

As for the Yermak, the care which went into her design and construction is evidenced by the fact that on the 28th of August, 1933, this 50-year-old ship reached the point $83^{\circ}06'N$ $138^{\circ}24'E$, a record. (Zubov, page 62).

2) The privately financed expedition of Lieutenant G.Ya. Sodev called in the St. Phoca from Arkhangel'sk on August 27, 1912. Personnel included the geographer V.Yu. Vizé, the geologist H.E. Pavlov, the artist N.V. Pinegin and others. The plan of the expedition was to reach Franz Josef Land by sea, construct a base there, and then continue to the Pole by dog-sled.

In the Barents Sea the year 1912 was a very severe one for ice. The expedition could not get farther than the north coast of Novaya Zemlia, and wintered there in a bay at $76^{\circ}N$ $60^{\circ}E$ to which the name of Phoca Bay was given.

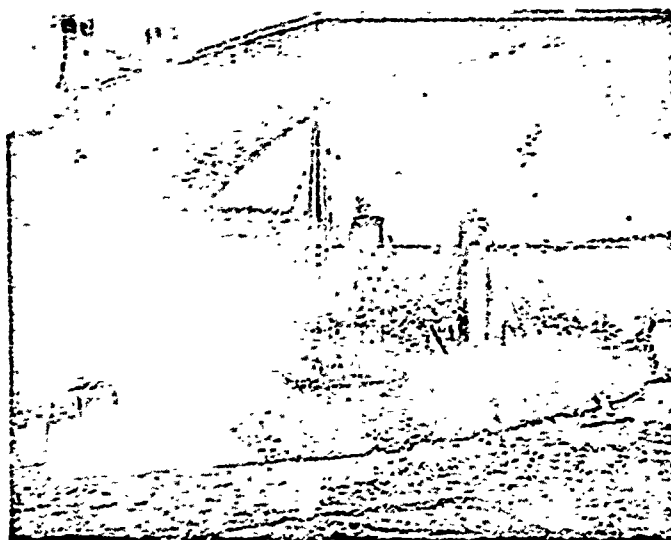
Only on the 3rd of September 1913 did the ice surrounding the vessel finally break up, and the ship continued to Franz Josef Land. The expedition wintered on Hooker Island. Supplies were becoming short.

In February 1914 Sodev, who by that time was weak and ill, set out by dog-sled for the North Pole, accompanied by two of his crew. He died en route, March 5, 1914. His two companions returned to the ship. The St. Phoca on her return voyage touched at Cape Flora to replenish her fuel with wood from structures built by the Jackson Expedition in 1894-97 and there picked up Al'banov and Konrad of the Brusilov Expedition. She limped back to Arkhangel'sk on the 28th of August 1914. (Zubov, pages 87-89).

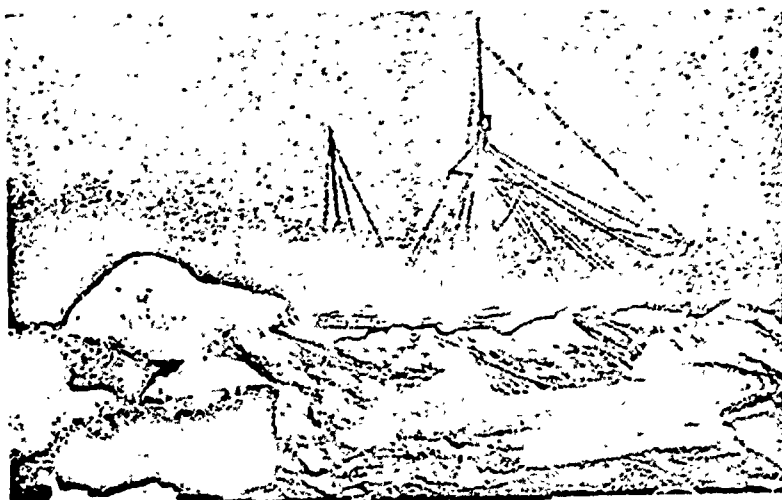
3) In the autumn of 1912, Lieutenant G.A. Brusilov's Expedition in the St. Anna, the purpose of which was to make the passage of the Northern Sea Route, was caught in the ice in the Kara Sea off the Yamal Peninsula, and from there was carried to the region north of Franz Josef Land. On April 23, 1914, when the ship was at $83^{\circ}17'N$ $60^{\circ}E$, eleven men headed by the V.I. Al'banov left the ship and went on foot over the ice to Franz Josef Land. Only two of them reached Cape Flora on Nordbruk Island (July 22), where they were picked up by the St. Phoca.



S.O. Makarov.



The Ice-breaker Yermak.



The Phoca in the ice.

Scientific Fisheries Expedition did not find in northern waters in 1900-1906 now exist there in great numbers. On the basis of these facts Knipovich says:-

"In about a decade and a half, or perhaps in even a shorter time, a change of such magnitude has taken place in the distribution of marine fauna that it would ordinarily be regarded as indicating a long geological period."

Closer investigation has shown that the climate of Europe is becoming more continental in character, a change which manifests itself principally in higher winter temperatures. For the last 50 years the atmospheric temperature in Europe has been steadily rising. Since the decade 1890-1899, the mean temperature at Leningrad has for instance gone up almost 1°C.

Even more remarkable is the fact that the warming of the Arctic is not a phenomenon limited to the single area of the Polar regions; it is on a scale affecting the whole terrestrial globe. Indeed you will find in Behring Strait and in the Pacific Ocean the same signs of a warming of the hydrosphere and atmosphere that you find in the Atlantic.

So far, it is not clear what causes lie behind the warming of the Arctic, nor how long this process is to continue. Many hypotheses ... more ingenious than trustworthy ... have been built around this point. The only thing of which we can be sure is that the warming of the Arctic is caused by a general stepping up of atmospheric and hydrospheric circulation, that is, by a vast exchange of air and water masses as between the Tropics and the Polar Regions.

Over the period 1920 to 1930 the atmospheric pressure in the Icelandic and Aleutian lows dropped on the average almost 5 millibars, and since the weight of the atmosphere has not altered, this means that over the subtropical high-pressure zone there has been a corresponding rise. Simultaneously there has been a rise in the amount of warm sea air flowing from the Atlantic to the Barents Sea and onward into the Arctic. This warm air is decreasing the amount of newly forming ice in these regions.

Stronger westerly and southwesterly winds in the North Atlantic mean a stronger flow of Atlantic water into the Arctic (both in surface currents and in deeper-lying currents), stronger winds along the Greenland Coast and a stronger efflux of water and ice from the Arctic. We have already noted that a rise in the temperature of the Atlantic waters definitely involves an increase in the speed at which they flow into the Arctic.

Available data on increases in the speed of the ice-drift are much less exact. One thing however it is essential to mention. In recent years Soviet marine expeditions have been casting large numbers of buoys adrift in the Greenland, Kara and Laptev Seas, for the purpose of studying the currents and the ice-drift. Many of these buoys were picked up later on the shores of Greenland, Iceland and Norway, and when the currents and drifts were calculated it turned out that every buoy since 1933 gave speeds three or four times greater than before 1933. As I have already stated, the drift-speed of Station North Pole was likewise 2.4 times greater than was expected. The Sedov drift started much farther south than the drift of the Fram, it ran considerably farther north, and it finished considerably farther south again.* Yet the Fram's drift

* See frontispiece Map II.

took 1055 days, while the Sedov's drift took only 812 days. From this it becomes evident that during recent years the Central Arctic Basin has been exporting an ever-increasing amount of its mighty ice-masses.

Thus an intensified general circulation in the atmosphere and hydrosphere, the final result of which has been a warming-up of the Arctic, may be regarded as a proven fact. This however is not an answer to the problem; it is only a replacement of one problem by another, for the question of what caused the increased circulation remains unanswered.

Warmings and coolings of the Arctic are phenomena which were long ago noted in the chronicles of mankind. Some scientists have tried to link them to astronomical phenomena. Thus Simpson is of the opinion that the periodic character of glacial and inter-glacial epochs can only be explained by successive changes in the amount of solar heat received by the earth. Clayton points to an influence of sun-spot maxima and minima (which have a period of 11 years) in determining the distribution of atmospheric pressure and consequently that of the precipitation.*

In studying the secular variations of the ocean level, the following two facts must be taken into consideration: First, there are noticeable differences between the annual mean levels at different parts of the ocean, especially in the case of the partly landlocked seas. Second, the annual mean level may show variations one way or the other over a large stretch of coast. This is of course a phenomenon most characteristic of the quasi-landlocked seas. Thus for instance over the whole coastline of the Baltic Sea, including its bays and sounds, the annual mean water-level was in the years 1891, 1897, 1901 and 1904 lower than the long-term mean, and in the years 1893, 1899 and 1903 it was higher than the long-term mean.

Recent American researches have shown that rises or falls in the annual mean level of the ocean take place over the whole coastline of the U.S.A., both on the Atlantic side and on the Pacific side. At all the Atlantic seaports the rises occur in the same years, and so do the falls, but they do not correspond with the high or low years on the Pacific Coast.

Special researches carried out by the French have shown that the secular fluctuations in sea-level are of periodic character and the principal period is 18.6 years, that is, the same period as the precession of the nodes of the moon's orbit. Other periods discovered in these researches were 8.85, 11.11, and 93 years; they also may be related to elements of the moon's rotation around the earth.

Thus we may regard it as indubitable that the secular variations in the level of the ocean, or of parts of it at any rate, are connected with cyclic variations in the tidal forces exerted by the moon and the sun.

* The fluctuations in the level of certain lakes, fluctuations which chiefly depend on the amount of precipitation, do indeed show a surprising agreement with the sunspot cycle. The level of Lake Ladoga is higher at the sunspot minimum, while that of Lake Victoria in Africa is on the contrary higher at the maximum, facts which may be explained by a difference in the distribution of atmospheric pressure at these lakes, caused by solar activity.

But variations in the level of the ocean, and variations which furthermore are simultaneous over great areas, involve displacements of enormous masses of water. Such displacements make our thoughts turn to the possible effect of the winds in piling up water or driving it back. If the surface waters of the sea are driven toward the shore they raise the sea-level there, and at the same time there is an increased efflux of the deeper waters in the opposite direction, out to sea. If the surface waters are driven away from the coast, these phenomena take place in reverse sense. A further point of resemblance between tidal movements and these on-driving and off-driving effects of the wind is that the comparatively small changes which they cause in the level of the surface may be accompanied by rises or falls of very great amplitude in the deeper-lying waters.

The phenomenon of waves in the deeper waters of the ocean, ebbing and flowing with the tides, first attracted attention when studies were being made of the seasonal fluctuations of salinity in the Denmark Straits. It was shown that the periods of this fluctuation were related to the periods of certain astronomical phenomena. Peterson, studying the secular fluctuations in the catch of fish in the Denmark Strait, found a period of 111 years, while Darcy Thompson found that the maximum catch at Edinburgh occurred every 13 to 16 years.

The longest astronomical period affecting the amount of ice in the Atlantic sector of the Arctic is, according to Peterson's researches, one of 1800 years. Every 1800 years the sun, the moon and the earth find themselves in the same plane and on the same straight line, under conditions such that the distance between earth and sun is a minimum. At such times the tidal forces reach a maximum, and consequently the greatest disequilibrium exists both in the atmosphere and in the hydrosphere. The heavenly bodies were in this configuration about 3900 B.C. and 2100 B.C., and again in the year 1433 A.D.

In the case of the latter date, the researches of Scandinavian historiographers have shown that great climatic and hydrological changes took place in the North Atlantic at about that time. As the Icelandic sagas tell, the Norwegian Vikings of the 10th to the 12th centuries had no trouble in sailing to Greenland in their frail ships.

In 984-987 A.D., Erik the Red sailed along the eastern coast of Greenland from Angmagssalik to Cape Farewell without meeting ice. Peterson thinks that in those days no ice came past Cape Farewell into Baffin Strait. The climate of Greenland was much the same as the present-day climate of Norway at the same latitudes.

From 1261 A.D. on, there appear the first documentary indications of Iceland blockaded by ice. Communications with Europe became so bad that the Norwegian colonies which Erik the Red had founded in South Greenland, and which had reached a flourishing state,* were in the 11th and 12th centuries falling into decay, to be finally destroyed by the Eskimos; the western group in 1341-1370 and the southern group (in the straits around Cape Farewell) in 1418 A.D.

* How flourishing these colonies were may be judged from the following facts: the western group of colonies counted 90 estates and 4 churches; in the southern group there were two cities with a cathedral, 11 churches and 3 monasteries.

Simultaneously with the ice-blockade of Iceland, they began to have very severe winters in Norway and there were catastrophic floods on the eastern shores of the North Sea.

Geological researches have shown that the climate of the Bronze Age (1700 - 600 B.C.) was milder than even in the days of the Vikings, and that a marked change in winter conditions took place in the 3rd and 4th centuries before our era. At that time too the shores of the North Sea were being devastated by floods. The severe winters of this epoch live in the Northland mythology under the name of the "fimbulvinter"; they were one of the causes of the first migration of peoples.

The problem of the warming of the Arctic is one of the first-line significance. The key to its solution is to be found in the Atlantic and in the Arctic itself. There is no doubt that the vast and diversified research being carried out nowadays by Soviet scientists is clearing the way toward the solution of this important problem.

IN CONCLUSION

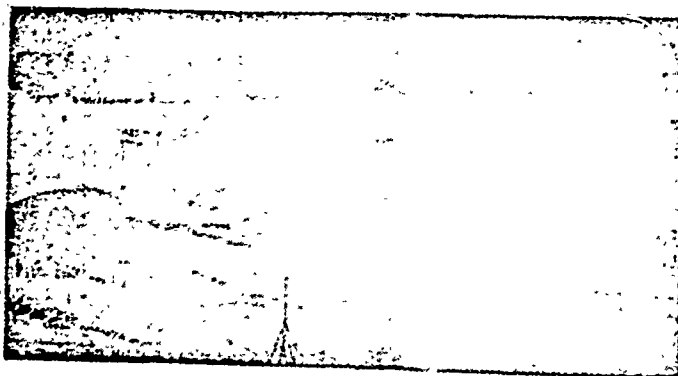
When we look back at the history of the exploration of the Arctic Lands, then in spite of ourselves we are amazed at how much has been accomplished, particularly by Russians and particularly during the Soviet period, toward the mastery of the Arctic. With profound gratitude and respect we remember those men, great and small, famous and obscure, who put so much stubborn hard work, endurance and effort into the exploration of the Arctic Regions, sometimes even yielding up their lives thereto.

But when we look ahead, we see how much there still remains for us to do, if we are really to know the Arctic.

To this day there are seasonal and secular variations of certain geographical factors of which we know nothing; there are important problems still unsolved, such as climatic fluctuations, the warming of the Arctic, and so forth. Even in the sector of the Arctic which has been best studied, that bounded by Greenland, the North Pole and the New Siberian Islands, there remains much that is unknown.

One therefore understands how the white spaces on the map of the Arctic attract and lure the explorer. One understands all the effort, the dream of reaching the very center of the Arctic. One understands why many of the Soviet Arctic explorers are dreaming of doing it all over again: drifts, winter sojournings and expeditions, this time with the aid of every possible means of locomotion, aircraft, ships and submarines; they dream of setting up on the ice fields of the Central Arctic the latest automatic devices ... self-registering instruments and radio transmitters.

Study of the Arctic is essential for the development and exploitation of its natural productive resources, for the understanding of the meteorological processes taking place over the greater part of the territory of Europe and the Soviet Union, for the mastery of the Northern Sea Route. This study is essential too for opening up the roads of the future ... the northern air routes uniting Europe and Asia with North America.



Arctic Station in Tiksi Bight.

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